MIDDECK ACTIVE CONTROL EXPERIMENT
(MACE)
Phase A Final Report

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Executive Summary

In 1988, the National Aeronautics and Space Administration began three separate and parallel efforts to investigate the feasibility of conducting on-orbit, closed-loop, structural dynamic experiments on test articles incorporating Controlled Structures Technology (CST). The three programs are:

- Controls, Astrophysics and Structures Experiment in Space (CASES) managed by the Marshall SpaceFlight Center. This experiment consists of a pinhole occulter facility using of a 105 ft truss deployed from the STS payload bay.
- Remote Manipulator System-Based Control-Structures Interaction Experiment, managed by the Langley Research Center and conducted at the Charles Draper Laboratories. Its goal is to enhance the performance of the STS RMS by employing active control techniques to damp undesirable vibrations. The experiment will attach additional sensors along the length of the RMS in order to obtain data that will be used to control the vibration of the arm while a large mass is attached at the end.
- Middeck Active Control Experiment (MACE), managed by the Langley Research Center and conducted at the MIT Space Engineering Research Center (SERC), which is the subject of this report.

The grant for MACE was awarded to MIT on November 1, 1988 with a planned program duration of six months. Previously, MIT SERC had been awarded the phase B contract for a similar middeck experiment, the Middeck 0-g Dynamic Experiment (MODE). Unlike MACE, MODE is an open-loop experiment; no closed-loop control is currently envisioned. The MODE program consists of two separate parts. The first is to develop a facility for conducting structural dynamic tests on-orbit in the STS middeck. The second objective is to design and test two separate test articles: The first article is a small fluid container mounted on a force balance and has as its goal to investigate the dynamics of fluid-structure interaction in zero gravity. The second test article consists of a jointed truss structure and will investigate the open-loop dynamics of structures in zero gravity and compare these results with ground test data. These two test articles are combined in one program because they both require similar experimental support equipment. In other words, both test articles could be tested with very little additional cost.

MIT SERC was awarded MACE in part because of the obvious similarities between both programs. Since MACE can be thought of as a follow-on to MODE, the same

engineering team was assigned to both programs. Like MODE, the goal of the MACE is two-fold. First, the program will provide NASA with a facility and a capability for conducing closed-loop experiments on structures inside the STS middeck. This facility will be available for use on subsequent flights, and a wide variety of test articles will be able to make use of it. Second, a structural test article will be designed and flown, and the associated ground tests and post flight analyses will be performed. The goal of this portion of the program is to obtain valuable scientific data which can be used by NASA in the design of future spacecraft that will require Controlled Structures Technology to meet their mission objectives. These two objectives are illustrated in Fig. 1.

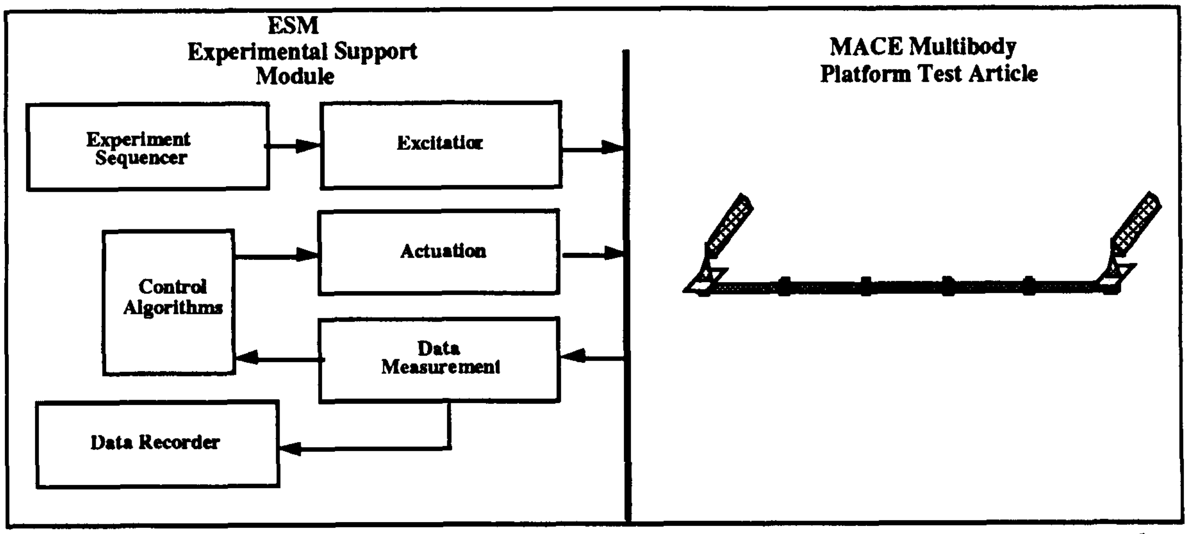

Figure 1 Schematic showing the functions of the two objectives of the MACE program: the experimental support module and its associated functions and a multibody platform test article.

This grant, which corresponds to the Phase A portion of MACE, had the following goals:

- Develop a rationale that explains the need to conduct on-orbit, closed-loop experiments on structures that are to be deployed in space.
- Examine the capabilities and limitations of the STS middeck for the conduct of on-orbit, closed-loop experiments.
- Conceptually design two test articles and an experimental support module that can be tested inside the STS middeck.
- Develop a program plan for the entire project through post-flight analysis, including cost estimates using one of the test articles as a reference design.

These four goals were successfully accomplished and the relevant conclusions will now be summarized.

On-orbit, closed-loop experiments on structures incorporating CST need to be performed if the differences that exist between the ground and orbit environments give rise to unmodellable uncertainties in either the open or closed-loop models of the structure. These unmodellable uncertainties can be though of as singular perturbations, if their effect on the structure does not disappear as the perturbation approaches zero. Therefore these perturbations can not be simulated on earth. In addition, there may exist regular perturbations whose effects, while predictable, may modify substantially a particular structural parameter. For example, small changes in the plant can often lead to large changes in the modal damping and in the mode shapes, two quantities that have a direct and substantial effect on closed-loop stability and actuator/sensor performance.

In order to identify whether these perturbations exist, it is likely that on-orbit open-loop testing of the structure will be required. However, even if no perturbations of the type described above are identified, it has been demonstrated that no measures of accuracy of the open-loop model are sufficient to guarantee stability of the closed-loop system at an arbitrarily high gain. In addition, open-loop testing should be accomplished using the sensors and actuators that will be used in closing the loop. Therefore, if it is necessary to conduct on-orbit open-loop tests in order to investigate the presence of any unmodellable or undesirable perturbation, it may be advantageous to also perform the closed-loop tests since the additional incremental costs will be small.

Having determined that on-orbit closed-loop testing will probably be required, a study of the STS middeck was undertaken to establish its suitability as a test site for conducting these experiments. The study revealed that the volume constraints and gravity environments of the middeck are adequate. The ability of the astronauts to work in a shirt-sleeve environment with the test article and thereby be able to modify or repair components that may malfunction, are characteristics that are only available on the middeck. The presence of an atmosphere, along with the lack of viewing ports and the added safety concerns due to the presence of the astronauts, does restrict the types of test articles that may be used. More importantly, however, two issues were found to have a significant impact on the mace test article design and testing sequences:

- *Data up/downlink.* Currently, there is no capability available on the middeck for data transfer between the ground and the Orbiter.

- *Power.* Currently, middeck payloads are restricted to 115W of power. Additional power must be negotiated with Johnson Space Center.

Possible solutions to these two problems have been identified. Data downlink may be accomplished using the Orbiter video signal channel for small amounts of time. Additional power will be available to all middeck payloads once the Middeck Accommodations Rack (MAR) is installed in the near future. Alternatively, batteries could be used to augment power, though this option does increase safety and heat dissipation concerns. All of these possible solutions will be pursued in the subsequent phases of the program. The reference design presented in this study, however, does not rely on either of these events occurring, but would take advantage of them if they were to become available.

Finally, since the middeck does offer a restricted volume in which to conduct experiments, a scaling analysis of the closed-loop system was performed. Once the scaling laws governing the experiment are understood, results obtained on the middeck test articles can be extrapolated to full-scale spacecraft. The test article, the computer, the disturbance environment, and the performance metrics were analyzed to determine if any parameters would not scale appropriately. Though some disturbances such as the gravity gradient torque and performance metrics such as the surface tolerance on reflective surfaces would present problems in scaling, the analysis shows that the scaling laws governing closed-loop experiments are well understood and no substantial problems associated with scaling-up any test results obtained as part of MACE exist.

Having established both the rationale and the scaling laws for conducting on-orbit, closed-loop experiments on the middeck, a survey of proposed NASA missions was undertaken to identify candidate test articles for use in MACE. The survey revealed that potential test articles could be classified into one of three roles. Test articles whose technology was in its early stages fulfill a *development* role since their primary purpose was to aid in the definition and expansion of the technology. Test articles whose mission definition was more evolved were identified as being *demonstration* experiments, since their primary purpose was to demonstrate the viability of the technology to potential users. Finally, test articles whose primary function was to aid in the certification of a spacecraft so that it would successfully fulfill its mission were identified as fulfilling a *qualification* role. A set of criteria was derived that allowed determination of which role a potential test article fulfilled. These criteria were applied to a set of five test articles draw from a survey of future NASA or DoD missions. From this set of five, two test articles were selected. The first is a development test article consisting of a multibody platform (MBP). The three-dimensional behavior of such a structure, along with the time varying dynamics associated

with payloads undergoing large angle maneuvers, and the low structural frequencies of the supporting bus, make such a structure extremely difficult to test on earth. The second is a scaled-down version of the STS Remote Manipulator System that would be used to expand the operational envelope of the RMS. Such expansion cannot easily be done on the full-scale structure due to Orbiter safety concerns. However, envelope expansion is absolutely required if the RMS is to fulfill its currently envisioned roles during the assembly of the proposed NASA Space Station. A scaled RMS would therefore a qualification test article.

Reference designs were developed for both test articles. For the Scaled RMS, the various structural components of the manipulator were scaled in a manner so as to increase the structural frequencies by 2.5, while reducing the overall size of the structure by a factor of 8 in order to accommodate the middeck volume. In addition, the computer requirements were estimated, and an analysis was performed to determine the ground-based behavior of both the full-scale and sub-scale RMS.

For the MBP (Fig. 2), a survey of future missions identified numerous types of disturbances and payloads that could be mounted to a platform. Therefore, a modular design was adopted to permit numerous configurations and payload combinations. The reference design consists of two pointing/tracking payload mounted on a 1.5 m segmented tubular bus structure. A two axis motor/gimbal on each payload controls the orientation. Angular rate gyroscopes mounted on the payload would be used to determine its angular orientation. In addition, an induced strain actuation segment would be located on the bus between the two payloads. Finally, other attachments such as proof mass actuators, dampers, or additional accelerometers could be mounted at various locations along the structure.

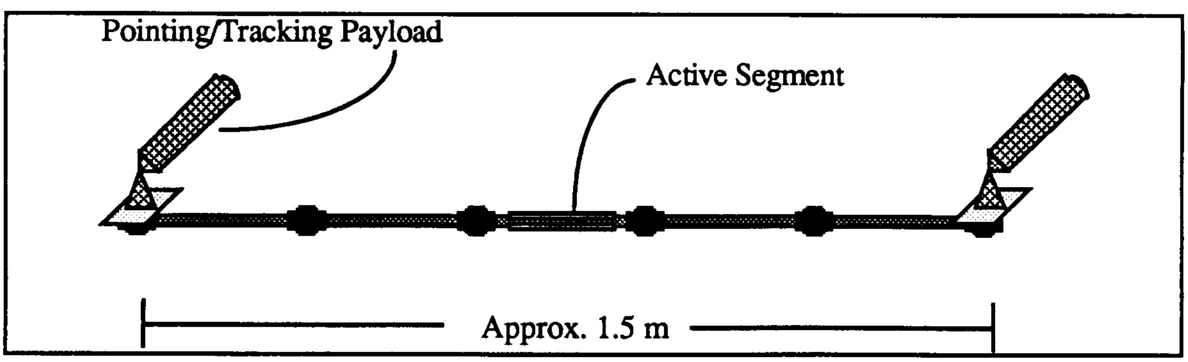

Figure 2 Multibody platform reference design

Computing requirements for running typical closed-loop controllers were determined, and various computer configurations were studied. The various components

required to manufacture the structure were identified, and a survey of commercially available products revealed no unexpected difficulty in obtaining satisfactory instrumentation.

A test sequence was developed which addresses the two fundamental problems faced by multibody platforms: performance in the presence of structure-borne disturbances and performance in the presence of other actively controlled payloads. The payloads will be sequentially used in angular pointing, tracking, and random input modes in order to examine both of these issues. The on-orbit tests would be duplicated on the ground during both the pre- and post-flight phases of the program. This ground test program is required in order to obtain the maximum amount of scientific return from the STS flights. The ground testing is essential in order to address the critical technology issue presented by MACE: can closed-loop control algorithms be designed and *implemented* on non-linear flexible bodies with articulating payloads and time-varying dynamics? It is the need to answer this question before committing to the expense and difficulties of performing a flight experiment that necessitates an aggressive ground-test program.

In order to adequately support the experiment and the NASA payload integration requirements, a management team has been established for the remainder of the program. The team was broken into three separate areas: experiment development, flight and ground systems development, and integration to the carrier. A work breakdown structure for the program was developed and specific jobs and responsibilities have been assigned to each member of the team. Procedures for configuration control, fiscal control, and safety, reliability and quality assurance have been developed.

A three and one-half schedule is proposed for the entire MACE program, leading from the Phase B ground-test development to the post-flight analysis (Fig. 3). The schedule identifies the major milestones that occur through the life of the program. Interaction with the NASA Johnson Space Center integration staff, as well as with the Astronaut office in order to establish crew training procedures, has already begun, and is reflected in the schedule. The total cost of the program up until the end of the post-flight analysis phase is $6 million. This cost reflects the requirement that, in order for MACE to achieve a valuable scientific return, it must be coupled to a vigorous ground test program, whose cost is included in the above figure. As demonstrated earlier, all proposed on-orbit experiments require such a ground test program before they can be considered candidates for flight on the middeck.

Chapter One: Introduction

The problem of exerting control on large or precision flexible structures has, in recent years, been the focus of a broad research effort throughout the aerospace engineering community. Many presently planned and future space missions such as space-based interferometers or earth-observing satellites exhibit the need for both an increase in pointing accuracy and a simultaneous reduction in their structural mass and associated stiffness. A possible way of reconciling these two conflicting requirements is through the use of active control to increase the damping or alter the static and dynamic shape of the structure. The use of active control techniques in highly flexible structures with closely coupled modes within the controller bandwidth is referred to as Controlled Structures Technology (CST).

A large amount of analytical work has been accomplished in this field. Many control techniques presently exist which can, at least theoretically, design stable active control algorithms to meet achieve required performance objectives on systems where the flexibility of the structure cannot be ignored. However, implementation of these controllers on actual space structures has not been widespread. The reasons for this are two fold. First, theoretical control schemes which work well on paper often encounter numerous problems during implementation. The low energy dissipation characteristics of space structures, the inability to obtain adequate finite-order models of the structural plant, the unavoidable presence of measurement noise, along with the "real-life" sensor and actuator dynamics often ignored in theoretical formulations, all serve to greatly complicate the control implementation. Second, ground testing of space structures can often be difficult and costly, if not impossible. The differences between the ground and orbit environments can lead to a lack of confidence that ground-based experimental results are directly applicable on-orbit. It is not surprising, therefore, that spacecraft designers have often avoided implementing a CST solution to a problem, either by filtering the control system in the frequency region of a particular flexible mode, or rolling-off the active controller before the flexible modes appear. However, as spacecraft become larger and more flexible, these techniques will prove inadequate.

The Middeck Active Control Experiment (MACE) attempts to help resolve some of these issues. There are two goals to this program. The first is to provide NASA with a facility and a capability for conducing closed-loop experiments on structures inside the STS middeck. This facility will be available for use on multiple flights, and a wide variety of

test articles will be able to make use of it. Second, a structural test article will be designed and flown, and the associated ground tests and post flight analyses will be performed. The goal of this portion of the program is to obtain valuable scientific data which can be used by NASA in the design of future spacecraft that will require Controlled Structures Technology to meet their mission objectives. These two objectives are illustrated in Fig. 1.1.

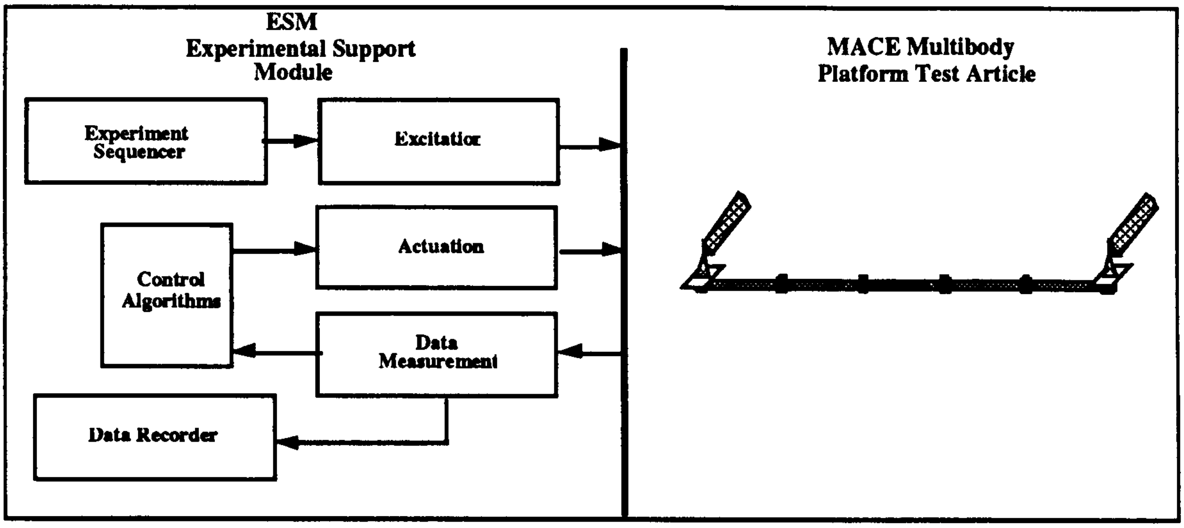

Figure 1.1 Schematic showing the functions of the two objectives of the MACE program: the experimental support module and its associated functions and a multibody platform test article.

In this report, which summarizes the MACE Phase A effort conducted by the MIT Space Engineering Research Center, the foundation for the successful accomplishing of these two goals has been laid. The report begins in Chapter 2 with the presentation of a coherent rationale that explains the need for on-orbit closed-loop testing for certain structural test articles. This leads to a set of criteria which allow the identification of these test articles and an understanding of the different purposes which may be served by the various test articles. Finally, the chapter concludes with a discussion of the scaling issues involved in testing structures on the middeck. Because of the limited space available inside the Orbiter, it is necessary to understand these issues in order that experimental results obtained as part of MACE be applicable to actual, full-scale missions.

In Chapter 3, a review of the STS middeck environment is presented. This was undertaken in order to understand the Orbiter capabilities and limitations, and to account for these in the design of the MACE reference test article. The detailed design of this structure is presented in Chapter 4, along with proposed flight operations and the associated ground test programs. This is followed in Chapter 5 by a description of the Experimental Support

Module which contains all the necessary equipment to perform an active control structural experiment on-orbit.

In Chapter 6, the management plan is presented. Included in this Chapter is a detailed work breakdown structure for the entire program leading to the first flight of the reference test article, the proposed schedule for the remainder of the program, and the proposed budget. The report concludes with various Appendices covering an assortment of technical issues.

Chapter Two: Rationale, Criteria and Scaling of On-Orbit, Closed-Loop Experiments

The goal of the MACE flight program is to conduct on-orbit, closed-loop experiments on test articles whose disturbance behavior and performance objectives require Controlled Structures Technology (CST). As a first step towards this goal, it is necessary to develop a structured methodology that can be followed to identify appropriate experimental articles for testing on the STS middeck. This *rationale* will serve to explain why it is necessary to conduct on-orbit, closed-loop experiments. This rationale leads to the development of *criteria* which can be applied to various potential test articles to select those which fulfill a necessary function in the development or implementation of CST. As part of this MACE study, a variety of potential test articles will be selected that are typical of present or future space missions which would be enhance or enabled through CST. Depending on how they meet the derived criteria, two of these potential test articles will be selected as the final candidates for the MACE program.

2.1 RATIONALE

In deriving a consistent rationale for justifying in-space experiments on actively controlled structures, one approach is to examine the available options for verifying the stability and performance of structures employing CST. A number of different options exist. The first and least expensive is to rely on analysis for the design and qualification of spacecraft which incorporate CST. Unfortunately, this approach is far less than satisfactory. The scientific literature is riddled with examples of both closed and open-loop experiments whose performance varied greatly from that predicted by state-of-the-art analytical methods. The reasons behind this are varied, and range from unmodelled dynamics of either the structure or the associated actuators and sensors, to the presence of a low signal to noise ratio in the measurements which can degrade the performance of the active controller. These results are well known and will not be listed here in any detail, but are simply brought to attention to illustrate that analysis alone is not sufficient.

The question that next arises is what sort of testing needs to be performed, along with analysis, in order to adequately verify Controlled Structures Technology for use in a zero gravity environment. Four different options exist. Listed in ascending order from lowest to highest cost and complexity, they are: ground-based open-loop experiments,

ground-based closed-loop experiments, on-orbit open-loop experiments and on-orbit closed-loop experiments. In the remainder of this section, these options will be addressed individually, and their advantages and limitations will be presented.

Ground-based open-loop testing is the simplest type of experimental program that can be carried out to verify the validity of analytical models. It is an absolutely necessary step, since the quantities that are most required for closed-loop control design are exactly those which are hard to predict analytically. For example, structural modal frequencies can be predicted using numerical methods with a relatively high degree of accuracy. Conversely, modal damping values are extremely hard to predict analytically on large complex structures where many energy dissipation mechanisms are present. Unfortunately, closed-loop controllers for structures usually require knowledge of the modal damping to a high degree of accuracy since knowledge of this value is required to obtain accurate predictions of stability margins and performance. These same controllers typically are more insensitive to a lack of knowledge of the modal frequencies. This problem is exasperated in structures that are lightly damped, such as those typically associated with Large Space Structures (LSS).

It is easily concluded, therefore, that ground-based open-loop testing is essential to quantify the accuracy of analytical models. However, these tests by themselves are not sufficient to validate the appropriateness of an analytical model or the performance of a closed-loop system. Skelton has demonstrated that no measures of accuracy of the open-loop model are sufficient to guarantee stability of closed-loop system at arbitrarily high gain. If the forces acting on a structure arise from a feedback controller, then the validity or appropriateness of a model cannot be quantified simply based on the open-loop response, since the importance of modelling errors depend on the amplitude and bandwidth of the control forces. This implies that open-loop testing needs to be done using the "closed-loop" sensors and actuators.

This reasoning implies that the acquisition of the open-loop model can never be sufficient to predict closed-loop performance, irrespective of whether the model was obtained using analytical or experimental methods. In addition, it is often difficult for structural dynamicists to quantify inaccuracies in a model, and for control designers to specify robustness norms, since these often depend on "real-life" actuator and sensor dynamics and geometries. Therefore, ground-based closed-loop testing is absolutely necessary for the successful application of CST to realistic structures.

In designing laboratory experiments, it is always necessary to accurately reproduce those phenomena whose presence significantly influences the measured result. Since CST, structures will be used in the space environment, it is important to investigate whether those characteristics that are present on-orbit and cannot be adequately simulated on-earth are important to the result of the open and closed-loop tests. The differences between the on-orbit and ground-based environments can change both the homogeneous description of a structure , *i.e.*, the stiffness, damping, mass, kinematics, and the non-homogeneous forcing that is applied on the test article. In Table 2.1.1, these various terms are given along with the four significant differences that are present between on-orbit and ground-based tests. Below each quantity in the table it is noted whether it has any effect on the corresponding structural parameter.

Table 2.1.1 The various structural, kinematic and dynamic parameters that can differ between on-orbit and ground tests.

	Aero/Acoustic	Suspension	Gravity	Thermal/Radiation
Stiffness	no	yes	yes	yes
Damping	yes	yes	yes	yes
Mass	yes	yes	no	no
Forcing	yes	yes	no	no
Kinematics	no	yes	yes	no

It is not surprising that the earth environment perturbs the structural parameters. The important issue, however, is whether this perturbation is *regular* or *singular*. A singular perturbation is one whose presence substantially modifies the structural parameter even as the perturbation approaches zero. This is in contrast with a regular perturbation whose affect on the structural parameter disappears as the perturbation is allowed to approach zero. If the perturbations on the structural parameters that appear when the test article is placed in a 0-g environment are regular, then they can be modelled and the results from the ground-based open-loop structural identification tests can be more easily interpreted and applied to the environment that exists on-orbit. However, even if the perturbations are regular, they may still have a very substantial, although predictable, affect on the structural parameter. For example, small changes in the plant can often lead to large changes in the modal damping or in the mode shapes, two terms that have a direct effect on closed-loop stability and actuator and sensor performance. Therefore, if the plant is highly sensitive to regular perturbations due to influences on Table 2.1.1, it is probably necessary to conduct open-loop on-orbit testing. If the perturbations are singular, then this is more difficult and it is then undoubtably necessary to conduct open-loop testing on-orbit in order to identify the real structural model.

For these reasons, since it is possible that significant differences may exist between the ground-based and on-orbit open-loop behavior of a structure, it is probable that on-orbit open-loop testing will be required for CST structures with high performance, closed-loop control. The only issue that now remains to be addressed is whether on-orbit closed-loop testing is still required, or whether the combination of ground-based closed-loop testing and on-orbit open-loop structural identification is sufficient to accurately predict the closed-loop performance of CST structures. The answer to this question depends on whether any singular perturbations are identified during the on-orbit open-loop experiments, or whether any regular perturbations cause significant unmodellable changes in the plant. If the answer to either of these questions is "yes", then on-orbit closed-loop testing is essential.

A preliminary analysis does not reveal any singular perturbations arising from one of the four sources shown in Table 2.1.1. Non convective potential aeroacoustic equations do not give rise to singularities, nor do conservative fields such as gravity. So long as suspension devices are passive or collocated active, they do not introduce singularities. Since the thermal/radiation terms only affect otherwise symmetric stiffness and damping parameters, they also do not give rise to singular perturbations.

However,a situation in which a regular perturbation can have significant effect on the closed-loop performance of the structure can be easily imagined. The stiffness added by a suspension system, even if small, can subtly change the modal structure. Additionally, for an articulated test article, a suspension system could introduce an unexpected kinematic constraint. Gravity can change preload on a joint, and hence damping. Gravity will also cause otherwise straight members to curve, causing significant changes in the modal structure, such as nonplanar coupling of modes. Therefore, while no singular perturbations have been identified, there are a number of regular perturbations which can cause sufficient changes in the plant that result in control performance being degraded.

In addition to changes in the plant, it may be useful to conduct on-orbit closed-loop tests for other reasons. First, it may be impossible to obtain an adequate performance metric on the ground for the particular mission which the spacecraft has to fulfill. For example, on-orbit interferometric payloads whose function is to look at electro-magnetic wavefronts from distant, dim stars may not be able to be adequately tested on the ground due to atmospheric distortion or the desire to observe in the ultraviolet range. Another situation which may justify on-orbit closed-loop testing is if the disturbance environment cannot be adequately simulated on earth. This situation could exist, for example, in spacecraft which require extremely low-noise environments which may not be able to be

adequately simulated in the laboratory. Finally, on-orbit closed-loop experiments may be justified from an economic argument. As was shown previously, it is necessary to use sensors and actuators in the "closed-loop" locations when doing open-loop tests in order to achieve adequate results. If these sensors and actuators are already in place for an on-orbit open-loop test, then the amount of effort required to close the loop might be small in comparison with the cost of flying the payload on the shuttle.

Therefore, the conclusion that is reached is that ground-based open and closed-loop testing is not sufficient for the verification of CST technology. At a minimum, on-orbit open-loop testing would need to be conducted to test for the presence of any singular perturbations, or any undesirable regular perturbations. If these perturbations are found to exist, then on-orbit closed-loop testing becomes essential. If they are not present, then the closed-loop tests might still be need to be carried out if a suitable ground-based performance metric is unobtainable, or, more likely, if the additional cost of conducting the closed-loop experiments were incremental.

2.2 CRITERIA

Having decided that there exists a rationale for on-orbit closed-loop flight experiments, the next issue that needs to be addressed is what are the appropriate roles for these experiments. This section will identify what roles these experiments should fulfill in order to span the complete spectrum of technological maturity, and what criteria should be applied in selecting specific test articles for these various roles.

In identifying these roles, a parallel can be drawn between the CST experimental process and the more well-known wind tunnel flutter experimentation process. Models of aircraft or airfoils have been tested in wind tunnels in order to identify flutter boundaries for over 50 years. The most fundamental purpose was to aid in the *development* of the technology, *i.e.*, the goal was to understand the nature of the physical phenomena that causes flutter. Subsequently, as the technology matured, wind tunnel experiments were conducted in order to *demonstrate* the ability to predict the onset of flutter as a function of the airspeed and wing geometric and elastic properties. Finally, once a final aircraft design is selected,wind tunnel and flight tests are conducted using a wide range of angles of attack and velocity conditions in order to *qualify* the vehicle, *i.e.*, to clear and expand the operational envelope.

A parallel trio of roles can be identified for CST experiments. The first is to enhance the *development* of new technologies. The on-orbit experiment will serve to identify

advantages and limitations in the use of new techniques. The second role is to *demonstrate* the capabilities of the technology. The experiment will serve to demonstrate to potential users that the technology has reached a level of maturity and applicability. Finally, the third role is to supplement actual mission vehicle *qualification*. In this, a scale-model of the structure would be used to help to clear or expand the operational envelope.

In order to classify candidate test articles into one of these roles, a set of criteria that can be applied to the test articles has been developed. They will be listed here in the form of questions that can be asked about each of the test articles.

First it is appropriate to list certain general criteria which any potential test article must satisfy before it can even begin to be considered for use as a candidate for on-orbit closed-loop testing as part of the MACE program:

- Is the flight experiment part of a coordinated program which includes analysis, ground experiments, and simulated zero gravity experiments, which has a high probability of making a unique and substantive technical contribution?
- Is the experiment cost effective and planned to easily integrate into the Shuttle middeck?
- Is the investigator prepared to spend a significant fraction of his/her career on the project?

Satisfaction of these three criteria serves to insure that only well-developed, cost-effective experiments which are closely coupled to an extensive ground test program are flown. A negative answer to any one of these questions is sufficient to disqualify a proposed test article from consideration as a flight experiment.

Once a test article has satisfied the general criteria, it can be considered for on-orbit testing on the Shuttle middeck in one of the three roles that have been previously identified. In order to identify the particular role that the testing of a test article would fulfill, a set of criteria for each role have been developed. Depending on how these are satisfied by the potential test article, it can be considered a candidate for the fulfillment of one of the roles.

For the *development* role, the additional criteria are:

1) *Does it enhance or enable technology for near, intermediate, or future, long term NASA or DoD missions?* Only missions that are of scientific or national interest should be tested.

2) *Has the technology developed sufficiently to identify potential real problems?* Shuttle experimentation is sufficiently expensive and complex that some understanding of anticipated technology problems and challenges must be incorporated. The Shuttle is no place for "shot in the dark"-type experiments.

3) *Can the experiment be carried out to permit identification of "unknown unknowns" while still obtaining useful data on predicted behavior?* If unexpected behavior occurs, it is necessary to have alternatives built into the testing program in order to obtain at least some useful data.

4) *Can mission typical environments,disturbances and performance metrics be identified and if so can they be sufficiently approximated on the middeck such that if associated problems exist, they will manifest themselves?* Only missions that require the 0-g environment of the middeck in order to properly perform should be tested.

5) *Can procedures for on-orbit testing and data analysis be developed that permit the use of the middeck as an on-orbit laboratory?* The middeck has many advantages, but also many limitations, as a laboratory facility for CST experiments.

For the *demonstration* role, the additional criteria are:

1) *Does it demonstrate a capability of intermediate or near term interest to NASA or DoD?* To be a candidate for this role, the technology that will be used in the mission must have progressed beyond the concept/definition phase.

2) *Has the supporting technology reached a level of maturity to provide solutions to identified problems?* If solutions have not yet been found, then the mission has not progressed enough to be considered for the demonstration role.

3) *Is there reasonable confidence that fundamental surprises can be dealt with?* All the fundamental problems should be understood and those that can directly affect the successful performance of the mission should have associated solutions.

4) *Can mission typical environments, disturbances and performance metrics be simulated on the middeck?* If this cannot be accomplished, then the mission should be tested outside of the middeck or on the ground.

5) *Can procedures for on-orbit,debug,and verification be developed such that the test provides adequate demonstration of the technology.* This creates confidence in potential users that the actual mission can be carried out on orbit.

Finally, for the *qualification* role, the additional criteria are:

1) *Is the test article matched to a presently approved flight program?* If the test article cannot satisfy this criteria, then it cannot, by definition, be a candidate for the qualification role since there is no actual mission that needs to have any qualification performed.

2) *If the purpose of the test is to define the initial operational envelope, are there any gains in time, cost or safety associated with the conduct of qualification tests on a scale model on-orbit? Or, if the purpose of the test is for expansion of the operational envelope, is there a reason why the tests cannot be carried out on the actual flight article?* If either of these questions is false, then it would be simpler or more cost-effective to carry out the tests on the actual flight article.

3) *Is there any uncertainty associated with the actual flight article?* If there is no uncertainty, then there is no need to carry out any scale-model tests.

4) *Can mission-typical environments,disturbances and performance metrics be duplicated?* It is important, since this is a qualification mission, to have available the disturbances and performance metric of the real mission.

5) *Can procedures be finalized for the conduct of on-orbit ID, debug, initial shape capture and fine-tuning to meet required mission specifications such that the actual mission is a success?* This will serve to certify the actual mission deployment and operational procedures.

None of the criteria listed above are absolute, but are generally an approach to categorizing possible test articles. For example,. a particular test article might not satisfy one of the criteria in one of the roles but still be considered a candidate for that role if it satisfies all the remaining questions.

It can be seen that the criteria listed above become more and more stringent as the technology level of the mission progresses. For example, question 1 in the *development* role simply states that the test article must be of interest to the engineering community. In the *demonstration* role, the criteria becomes more restrictive and the test article must be of at least intermediate interest to NASA or DoD. Finally, in the *qualification* role, the test article must be matched to an approved flight experiment or mission. This same parallelism exists for the other questions as well. The result is that while most test articles that will be considered will be able to satisfy the criteria for a *development* role, few will be able to satisfy all the criteria for a *qualification* role.

The above list of questions, coupled with the more generic questions listed previously, provide a framework with which candidate test articles can be judged. The next step is to identify these potential test articles. This will be accomplished in the next section.

2.3 POTENTIAL TEST ARTICLES

In all three of the defined roles for CST experiments, the initial criteria that has to be met by a proposed test article is whether it is of interest to a potential user such as NASA or DoD. Therefore, in compiling a list of candidate test articles, an appropriate place to start is by listing currently manifested or planned mission classes which might employ CST (Table 2.3.1).

Table 2.3.1 Planned NASA or DoD mission classes.

Astronomical
Earth Observing Multipayload Platforms
Robotic Manipulators
Planetary Explorers
Cosmology
Material Science
Communications
Military Specific

These classes are *functional*, and correspond to classifications such as bomber, fighter, transport, *etc.* for aircraft. Each of the classes listed in Table 2.3.1 can include a wide variety of missions with greatly varying characteristics. For example, astronomical payloads can consists of satellites with multipoint alignment technology (interferometric), deformable optics, segmented optics, etc. Therefore, it is more appropriate to classify these various proposed future spacecraft based upon their CST configuration (Table 2.3.2).

These configurations more clearly codify the CST goals and challenges of the missions. They correspond to aircraft classifications such as high aspect ratio, low aspect ratio, delta wing, *etc.*

Table 2.3.2 Planned NASA or DoD mission configurations.

Multibody
Single Point Alignment
Two Point Alignment
Multi Point Alignment
Surface Shaping (Segmented and Deformable Optics)
Microgravity
Large Dimension

Using the configurations of this list as guidance, a set of potential test articles can be selected. Initially, five potential test articles were identified which are meant to span the major CST issues, as well as potential experimental roles:

- *Multibody Platform*: This test article would investigate issues dealing with three-dimensional modal behavior, disturbance isolation, and multiple interacting control systems.
- *Flexible Articulating Structure*: Another multibody test article used to investigate the control issues of flexible manipulators with full, three-dimensional kinematics.
- *Interferometer*: A multipoint alignment structure, representative of future, space-based optical interferometers.
- *CASES scale model*: Scale model of the Control, Astrophysics, and Structures Experiment in Space, which is a two-point alignment, pin-hole occulter facility that will be deployed from the STS payload bay.
- *RMS scale model*: Scale model of the STS Remote Manipulator System, an articulated, flexible, multibody system, that can be used for expanding the operational envelope of the full-scale structure.

The general and role-specific criteria can now be applied to each of these potential test articles in order to determine which role they fulfill in a CST test program. The results of this process are given in Table 2.3.3

Table 2.3.3 Answers to criteria questions as they pertain to each potential test articles

	Multibody Platform	Flexible Articulating	Interfero-meter	Scale RMS	Scale CASES
DEVELOPMENT:					
1)	Yes	Yes	Yes	Yes	Yes
2)	Yes	Yes	Maybe	Yes	Yes
3)	Yes	Yes	Yes	Yes	Yes
4)	Yes	Yes	Maybe	Yes	Yes
5)	Yes	Yes	Yes	Yes	Yes
DEMONSTRATION:					
1)	Yes	Yes	No	Yes	Yes
2)	No	No	No	Yes	Yes
3)	No	No	Maybe	Yes	Yes
4)	Yes	Yes	No	Yes	No
5)	Maybe	Yes	Maybe	Yes	Maybe
QUALIFICATION:					
1)	No	No	No	Yes	Maybe
2)				Yes	No
3)				Yes	Yes
4)				Yes	No
5)				Yes	Yes

Obviously, the answers to many of the role-specific criteria are qualitative, and therefore disagreement on some of the resulting answers is possible. However, the general trends shown in the table and the conclusions that can be drawn are not likely to change. These conclusions are threefold. First, a scale model of the STS RMS would be an appropriate test article for the *qualification* role. The fact that the full-scale structure is currently flying and that real performance issues and measures exist make it the obvious candidate for scale model tests which would serve to expand the operating envelope for the full-scale test article. These envelope expansion tests cannot or would be more difficult to carry out on the full-scale structure because of safety concerns for the Shuttle and its crew. Yet the RMS capability must be expanded for Space Station assembly. For this purpose, a scale model in zero gravity is one alternative. The CASES scale model test article would not be a very good qualification experiment since it is not, as yet, an approved program and the scaling factors involved in order to fit the scale model on the middeck are so small such that it becomes much more difficult to manufacture the test specimen and extrapolate the results to the full scale structure. A scaled CASES would not even be a good demonstration test article due to the lack of the true performance metric required for the mission, *i.e.*, stars, on the middeck. The only role for which it seems to satisfy all the criteria is the development role. However, it is difficult to justify manufacturing a precision scale model in order to serve a developmental role when the full-scale program is underway.

The second conclusion that arises from Table 2.3.3 is that either the Multibody Platform or the Flexible Articulating Structure would be appropriate test articles in the

development role. The technology involved with either of them is sufficiently developed, and the ground-based testing issues are sufficiently complex, that on-orbit closed-loop testing is easily justified.

Finally, the interferometer test article does not appear to satisfy any of the three roles. This implies that the technology issues associated with a space-based interferometer are as yet not sufficiently developed to require on-orbit testing; an extensive ground-test program is required before a decision is made on whether on-orbit testing is required. It would seem, however, that if in the future a space-based interferometer platform is tested on-orbit, it would be more appropriate to test such a structure in an environment where the correct performance metric, *i.e.,* a star, is available and where atmospheric disturbances can be eliminated. Therefore, such a structure should probably be tested in the STS payload bay, and not on the middeck.

In conclusion, out of the initial list of five, two test articles, the multibody platform and the scale RMS, each fulfill one of the three experiment roles. The MBP is clearly a development test article, while the scale RMS is clearly a qualification test article. Further analysis can now proceed on these two test articles. Unfortunately, while it is possible to perform an initial scaling analysis on the RMS, it is quickly apparent that the design of such a structure is governed by the mechanical details of the various motors and joints making up the full-scale RMS. Therefore, while an analysis of the scale RMS was undertaken and is presented in Appendix A, it was the design of the mbp which was pursued in more detail, and was used for the purposes of costing and program timeline definition. The design of this test article is presented in Chapter 4. Finally, preliminary analyses on the test articles that were not clearly suitable for any of the three defined roles are presented in Appendix B.

Having completed the selection of the MACE test article, two issues need to be addressed before the detailed design of the multibody platform is undertaken. The first is that, given the volume constraints imposed by conducting the experiment on the middeck, it is necessary to understand how an active control experiment scales. This will allow results obtained from the MACE program to be extrapolated for use one full scale structures employing CST. An analysis of the scaling of active control structural experiments is presented in the following section.

Finally, the second issue that needs to be investigated is what are the capabilities and limitations of the middeck and how these affect the design of the test article. Power,

weight, and safety constraints must be understood before a detailed design of the MBP can proceed. This survey of the middeck capabilities is presented in Chapter 3.

2.4 SCALING OF MIDDECK TEST ARTICLES

The issue of how a test article scales is fundamental in the interpretation of most experiments. In the case of experiments performed on the STS middeck, the issue is extremely important due to the volume and weight constraints associated with conducting experiments on-orbit. It will probably be impossible to test structures of actual operational dimensions in the pressurized middeck environment. Therefore, it is important to understand how the experimental results obtained from the MACE program can be interpreted and applied in support of real spacecraft and missions.

The scaling of the MACE test articles is important in two ways. First, the test article might be a scaled down version of an actual space structure, which, for one reason or another, needs to be tested in sub-scale in order to confirm or expand the operational envelope. This occurs when the test article is designed to fill a *qualification* role. In this case, the design of the sub-scale test article must be accomplished so that the important structural dynamic and control behavior is accurately modelled. Alternatively, it is possible for the test article to be more generic, *i.e.*, to not be a directly scaled model of any specific full scaled space structure. This occurs when the article is designed to fill a *demonstration* or *development* role. In this case, the results obtained from the experiment will need to be scaled up in order to be applied to any specific, future spacecraft. Therefore, understanding of the scaling laws governing active control experiments is important either if the test article is a precision model of a specific spacecraft, or a generic model for development or demonstration.

Figure 2.4.1 shows a schematic of a typical active control experiment. Disturbances affect the plant which has an active control in a loop around it. A measurement is taken from the plant in order to quantify its performance. It is necessary to understand and develop the scaling laws as applied to each of the elements in that schematic: *plant*, *disturbances*, *controller*, and *performance metric*. It is not the purpose of this report to provide a complete derivation of the scaling laws for all possible active control test articles, but instead to identify the relevant scaling issues that need to be addressed in designing a particular active control experiment for flight on the middeck.

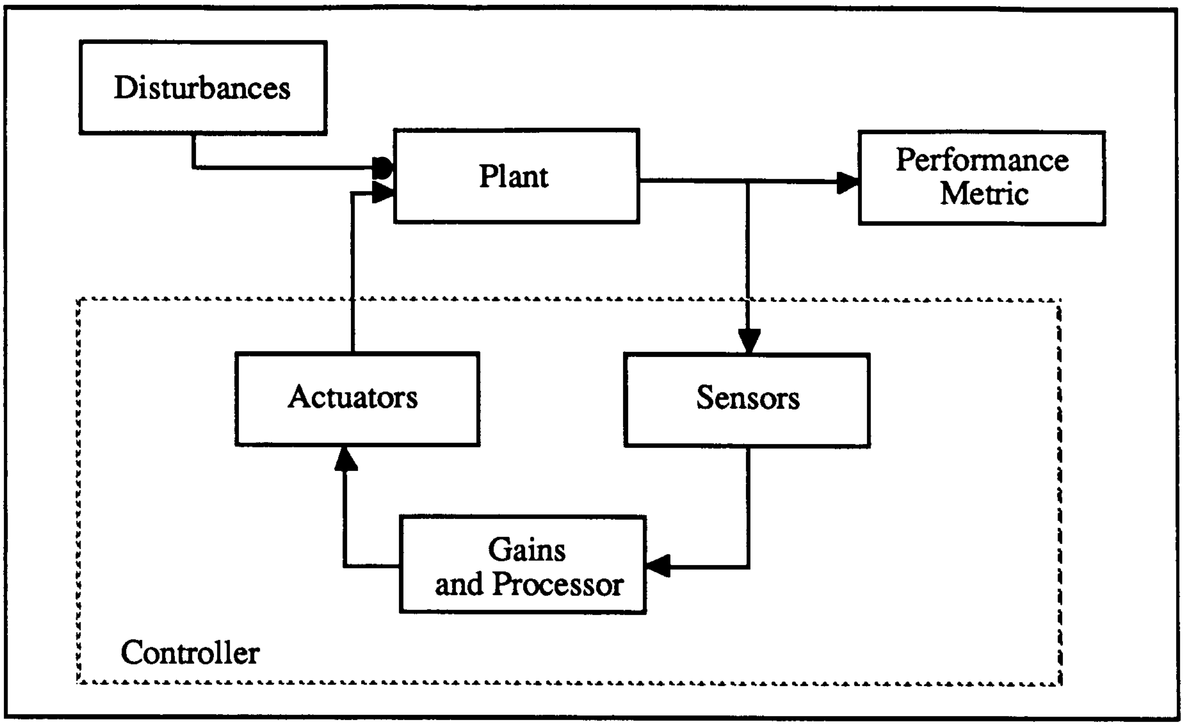

Figure 2.4.1 Block diagram showing the various components that must be scaled in an active control experiment.

2.4.1 Plant Scaling

The issues associated with scaling of structures have been well studied throughout the years in particular those with regard to aerodynamic applications. This is motivated primarily by the size constraints of testing scale models of aircraft or aircraft parts in wind tunnels. More recently, the issues associated with scaling large space structures have received attention due to the issues arising from the construction and deployment of the NASA Space Station. In this section, a brief overview on the methodology that is followed in deriving the replica scaling laws for a structure will be presented, followed by a brief listing of additional scaling schemes that can also be applied.

Replica scaling is the most common method of scaling of structures. A single scale factor λ is chosen so that the linear dimensions and deflections all scale with λ. The scaled test article is constructed from the same materials as the original structure, so that the density and modulus of both the test article and the full scale structure are equal. With these parameters set, it is now possible to use the differential equation that governs the behavior of the structure to derive how the remaining terms in the equation scale. For example, the differential equation governing a one degree of freedom system undergoing longitudinal vibration can be written as:

$$\rho V \frac{\partial^2 x}{\partial t^2} + \frac{EA}{L} x = F$$

Assuming that linear dimensions and displacements scale as λ and that ρ and E (density and modulus) scale as unity, the equation can be rewritten as

$$\lambda^3 \lambda \lambda_T^{-2} + \lambda^2 \lambda^{-1} \lambda = \lambda_F$$

where λ_T is the time scale factor and λ_F is the forcing scale factor. This equation can be simplified to

$$\lambda^4 \lambda_T^{-2} + \lambda^2 = \lambda_F$$

Since each term in the equation must be dimensionally consistent, it is seen that the forcing scale factor, λ_F, must be proportional to λ^2 and that the time scale factor, λ_T, must be proportional to λ. The implication of this analysis is that the any forcing on a scale model of a structure in longitudinal vibration must decrease as λ^2, while or associated time-dependent phenomena must decrease as λ. A similar analysis can be performed for other structures with additional homogeneous or forcing terms. The result of any analysis of this type is always to express the unknown scaling parameters in terms of the the previously chosen λ.

In replica scaling, a single scale factor λ was used in deriving the scaling laws for the structure . It is also possible to choose two separate parameters and use one for the geometric scaling terms and one for the force-frequency-displacement (L/FFD) or force-frequency-strain (L/FFS) terms. This is referred to as *multiple* scaling and can be used, for example, to obtain a test article which geometrically fits inside the middeck but whose frequencies are the same as those of the full scale structure. Finally, it is also possible to derive *hybrid* scaling laws for a structure. This method combines the multiple scaling factors of multiple scaling but distorts certain components such as the joints in a truss structure in order to appropriately model the dynamics of the individual components.

Table 2.4.1 shows the scaling factors for replica, L/FFD and L/FFS scaling. In summary, therefore, the scaling of the plant for the MACE project does not pose any difficulties that cannot be resolved by drawing from previous work.

Table 2.4.1 Scaling relations for various scaling methods.

Parameter	Scaling Factor	Replica Scaling	L/FFD Scaling	L/FFS Scaling
mass / length	$\lambda_{\rho A}$	λ^2	$\lambda^3\lambda_g^{-1}$	$\lambda^4\lambda_g^{-2}$
axial stiffness	λ_{EA}	λ^2	$\lambda\lambda_g$	λ^2
bending stiffness	λ_{EI}	λ^4	$\lambda\lambda_g^3$	$\lambda^2\lambda_g^2$
length	λ_L	λ	λ_g	λ_g
displacement	λ_δ	λ	λ	λ_g
rotation	λ_θ	1	$\lambda\lambda_g^{-1}$	1
time	λ_T	λ	λ	λ
force	λ_P	λ^2	λ^2	λ^2

2.4.2 Disturbance Scaling

In this section, the issues affecting how disturbances affect the structure will be discussed. The analysis required to scale the disturbances is directly analogous to that performed for scaling the structure. In fact, in the example presented in the previous section, it was shown that a point force scales as λ^2 under replica scaling. Therefore, any point force disturbance scales as λ^2. The implication of this result is shown in Fig. 2.4.2 The magnitude of point forces must decrease as λ^2, while the bandwidth must increase as $1/\lambda$, since the time scale is proportional to λ for replica scaling.

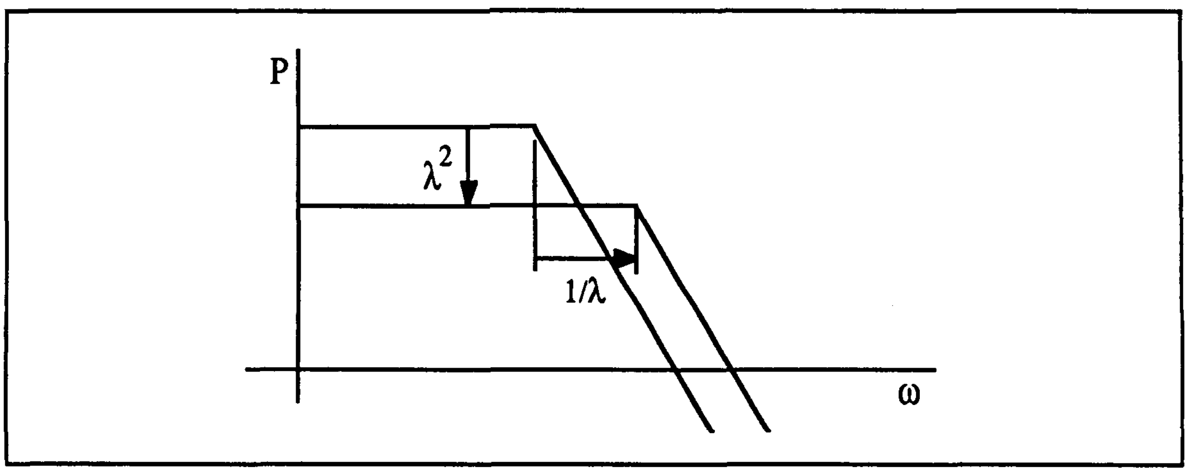

Figure 2.4.2 Replica scaling behavior of point force magnitude vs. frequency

Similar analyses can be performed for other types of disturbances: spanwise distributed forces (scale as λ for replica scaling), pressure forces (scale as unity), body forces (scale as λ^{-1}) and point moments (scale as λ^3). Table 2.4.2 provides a partial list of external, internal, and inertial disturbances which can affect a space structure. Where appropriate, a defining relation is listed next to the disturbance. If no relation currently exists, or if it depends on the details of the test article, the defining relation is omitted and

"?" is inserted. The next column indicates how the disturbance should scale for replica scaling. Finally, the last column describes the implication of the scaling analysis.

It is seen that the disturbances fall into one of four categories. First, some disturbances automatically scale as the structure is scaled. Inertial disturbances, for example, scale with the structure. A second category of disturbances are those which do not scale because of the inability to control one of the parameters in the defining equation. Gravity gradient torques are in this category since gravity at a given orbit cannot be changed. The effect of disturbances which do not scale on the test article must be evaluated, understood, and hopefully, minimized in their effect on the final measured results.

Table 2.4.2 Disturbance Scaling

Disturbance	Defining Relation	Should Scale as	Implication
EXTERNAL:			
Impacts	?	?	Simulate
Grav. Grad. Torque	$T \sim GMI_m/R^3$	λ^3	Doesn't scale
Solar Pressure	$F \sim cA$	1	Automatic
Air Drag	$F \sim \rho v^2 A$	1	Automatic
Electromagnetic	?	?	?
INTERNAL:			
Thermal	$F \sim EA\alpha\Delta T$	λ^2	$\alpha, \Delta T \sim 1$
Crew (Man)	?	λ^2	Simulate
Rotating Imbalance	$F \sim Me\Omega^2$	λ^2	$e \sim \lambda, \Omega \sim 1/\lambda$
Fluid Motion	?	?	Simulate
Acoustic	?	?	Simulate
CMG Noise	$F \sim Me\Omega^2$	λ^2	$e \sim \lambda, \Omega \sim 1/\lambda$
INERTIAL:			
Rigid Body Coupling			Automatic
Rigid BodyActuators			Automatic

A third class of disturbances are those which do not scale appropriately but can nevertheless be simulated. For example, disturbances arising from crew motion cannot be scaled since the size of the crew member is fixed. However, they can be simulated by measuring a typical crew disturbance spectrum, scaling it using the derived scaling laws, and inputting it into the structure with a mechanical actuator. Finally, the last class of disturbances are those which should scale with the structure, but because of manufacturing or other requirements actually do not. Disturbances arising from rotating machinery or gyroscopes are in this category since they depend on the eccentricity of the device. Since this is a linear quantity, it should scale as λ, but usually the eccentricity depends on the manufacturing tolerances used in fabrication of the device and it may not be able to be

specified to the accuracy required. Also, rotating equipment such as gyroscopes usually run at a predetermined angular velocity, and it is not possible to specify that this parameter scale as $1/\lambda$. As was the case for disturbances which could not be accurately simulated, the effect of this last class of disturbances on the test article must be examined for each particular test article.

Obviously, a similar discussion can be performed for scaling laws other than replica scaling. However, it can be concluded the the scaling of disturbances does not pose any difficulty, unless it is found for a particular test article that its behavior depends in a significant way on one of the disturbance types which cannot be accurately scaled. For this last case, if the test article could not be redesigned, scale testing of the structure may not be appropriate and full scale testing may need to be carried out. It is not expected, however, that for the types of structures proposed as part of the MACE program, that the scaling of disturbances will pose a problem.

2.4.3 Controller Scaling

In identifying the issues associated with the scaling of the controller in an active control experiment, it is useful to separate the controller into three components: actuators, sensors and processor. By identifying how the measurements and actuation scales, it is possible to derive how the gains in a controller must also scale.

Tables 2.4.3 and 2.4.4 show the various types of measurements and actuation that can be applied on a structure. These tables are not all-inclusive, since it is possible to obtain derived measurements and actuations by combining the various quantities listed, but for the purposes of the discussion in this section, the list provided in the tables will be adequate.

The two tables are divided into three sections. The leftmost section describes those measurements and actuations which can be thought of as being defined with respect to an inertial coordinate system or with respect to a coordinate system external to the test article. The middle section refers to actuators and sensors which are extensive and relative to another point on the structure. The last section refers to intensive and relative actuators and sensors, leading to differential quantities such as strain and stress.

For each type of measurement and actuation, a device which provides the quantity is listed. Some quantities cannot be directly measured or actuated, and the corresponding position in the table is left blank. Given a particular type of actuation and sensing, the appropriate scaling behavior can be found by performing the same type of analysis as was

presented for the plant scaling analysis. The measurement or actuation term simply needs to be inserted into the describing equation for the structure, and, as was done previously, the appropriate scaling term can be derived in terms of the scaling parameters. Once

Table 2.4.3 Measurements and sensor types available for CST experiments

Measurement	Inertial Reference	External Reference	Measurement	Sensor	Measurement	Sensor
L	-	(GPS)	$L-L$	LVDT, Interferometer, Inductive probes	ε	Strain Gauge
$\dot{L}$	-	-	$\dot{L}-\dot{L}$	LVT, Laser Doppler	$\dot{\varepsilon}$	Strain Rate Sensor
$\ddot{L}$	Accel.	-	$\ddot{L}-\ddot{L}$	-	$\ddot{\varepsilon}$	-
F	-	-	$F-F$	Force Sensor	σ	-
θ	-	(Star Tracker)	$\theta-\theta$	Potentiometer	γ	Strain Gauge
$\dot{\theta}$	Rate Gyro		$\dot{\theta}-\dot{\theta}$	Tachometer	$\dot{\gamma}$	Strain Rate Sensor
$\ddot{\theta}$	Angular Accel.	-	$\ddot{\theta}-\ddot{\theta}$	-	$\ddot{\gamma}$	-
M	-	-	$M-M$	Torque Sensor	τ	-

Table 2.4.4 Measurements and actuator types available for CST experiments

Measurement	Inertial Reference	External Reference	Measurement	Actuator	Measurement	Actuator
F	Thruster, Proof-Mass Actuator	Drag, Solar Pressure	$F-F$	Linear Motors, Hydraulic	σ	-
M	Momentum Wheel, CMG	Gravity Gradient, Magnetic Torquers	$M-M$	DC Motors	τ	-
L	-	-	$L-L$	Piezos, Lead Screws	ε	Piezos, Thermal, SMA, Elec/Magneto-Strictive
θ	-	-	$\theta-\theta$	Stepper Motor	γ	Piezos

the scaling laws governing the actuation and sensing have been derived, it is straightforward to deduce how the related gain should scale. For example, it has already been shown that point forces scale as λ^2 (for replica scaling) and that displacements scale as λ. Again relating a measured displacement to an applied point force must scale also scale as λ in order to satisfy dimensional compatibility of the feedback relation. Therefore, scaling of the feedback gains in a controller is determined by the scaling of a given actuator-sensor pair.

In addition to gain scaling, the temporal scaling of the compensation must be considered. Dynamic controllers and their associated bandwidths are governed by the scaling laws which determine how the frequency scales. For replica scaling, it was found that since time scales as λ, frequency scales as $1/\lambda$. The dynamics of the controller must therefore be appropriately scaled. Of course, the bandwidths of the actuators, sensors and digitization and computation rate of computers must also be scaled as $1/\lambda$. A complete accurately scaled design would also require that the analog to digital and digital to analog converters also be scaled to maintain the same resolution levels on the scaled test article as on the full scale spacecraft.

In conclusion, therefore, scaling of the controller does not pose any fundamental difficulties and can be performed in a straightforward manner once the scaled behavior of the actuation and sensing variables has been determined.

2.4.4 Performance Metrics Scaling

The performance metrics which can be applied to the structure can be divided into two categories: plant dynamic metrics (damping, disturbance rejection, step response, *etc.*) and system-specific metrics (jitter, alignment, line of sight, surface tolerance, *etc.*). Depending on the particular metric that will be used on a test article, it is straightforward to determine how the variable should scale for a given scaling method.

Generally, the plant dynamic metric will scale automatically. However, the possibility does exist for some system-specific metrics to not scale because they involve quantities which cannot be varied sufficiently. For example, surface tolerance on an optical device depends on the wavelength of the light that is being observed. When a one quarter scale mirror is build, its tolerance does not diminish by one quarter since it still must collect light.

In general, therefore, the performance metrics for a particular test article can be scaled the same analysis as presented previously. However, the possibility does exist for

some metrics to not scale appropriately, or to have practical limits on the amount that they can scale. These need to be evaluated for each individual test article.

In summary, scaling of closed-loop active control structural experiments does not appear to present any fundamental difficulties, apart from those related to the gravity gradient torques applied on the structure and those that utilize certain optical performance metrics. Therefore, a MACE test article can be designed to fit on the middeck, and data obtained from closed-loop experiments can be interpreted and applied to larger structures deployed on-orbit, as long as the two factors listed above are not significant. Before proceeding to a detailed design of the test article, however, it is useful to investigate in more detail the experimental environment presented by the STS middeck, in order to better understand its capabilities the limitations it imposes on any active control experiment.

Chapter 3: Opportunities and Limitations of the Middeck Environment

Performing MACE in the orbiter middeck provides advantages in several areas related to experiment cost, operation, and manifestability. However, the middeck environment also imposes several restrictions on volume, power, weight, and safety on the design of experiments that will fly on-board. It is important to be aware of these capabilities and limitations before proceeding to the detailed design of the MACE test article. These issues are addressed in this chapter, along with several important services available to middeck locker payloads.

3.1 ADVANTAGES OF USING THE MIDDECK

3.1.1 Physical Attachment and Power Supply

The recommended design of the payload uses the volume of a middeck locker as the primary carrier for the experiment electronics (see Figure 3.1.1). Lockers are located hard attached to avionics bays 1 and 2 (middeck forward), and to avionics bay 3A (middeck aft), as shown in Figure 3.1.2. The electronics will be packaged in a metal frame which slides into the locker. Middeck payload physical and structural interface design requirements are described in detail in NSTS 21000-IDD-MDK, "Shuttle/Payload Interface Definition Document for Middeck Accommodations", Sections 3 and 4.

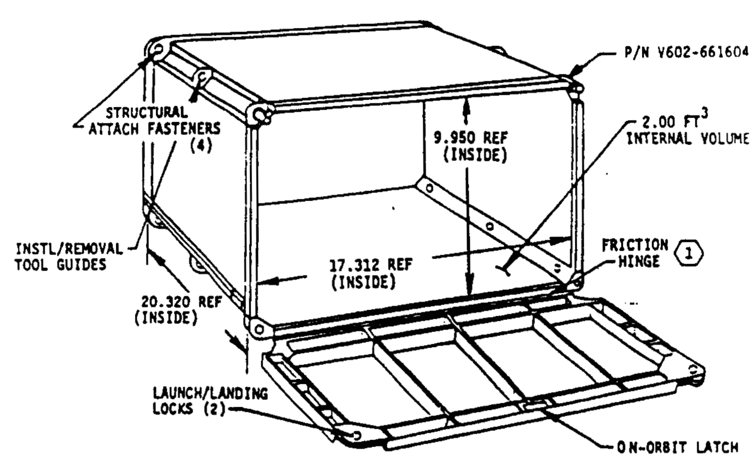

Figure 3.1.1 Standard Middeck Locker (source: NSTS 2100-IDD-MDK, p. 3-8)

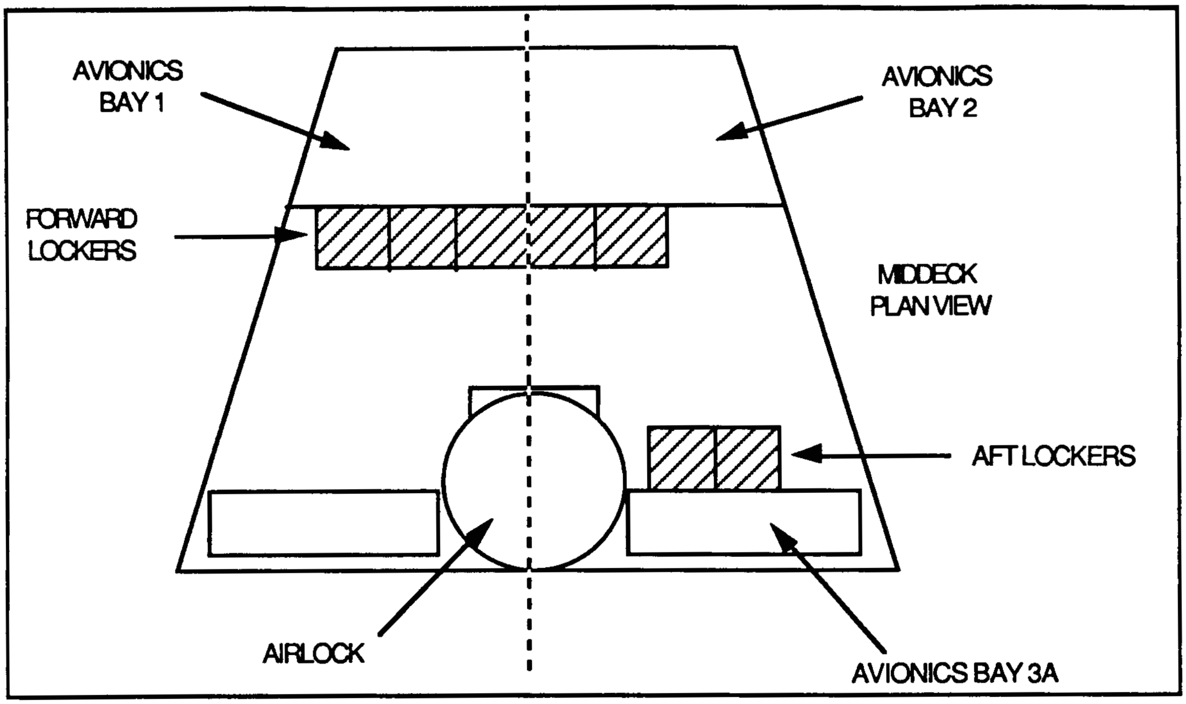

Figure 3.1.2 Middeck Layout (Source: NSTS 21000-IDD-MDK)

The orbiter provides +28 ± 4 VDC power from a middeck ceiling power panel via a standard NSTS provided umbilical. 115 watts of continuous DC power is available for any single experiment over an 8 hour period. Note that supply voltage varies with power consumption, and is generally lowest at full power drain. Electrical power interfacing is described in the IDD-MDK, Section 7.

3.1.2 Direct Crew Involvement

Direct crew involvement is a major service available to middeck payloads. The presence of an astronaut allows experiment protocols to be modified or updated during the flight, rather than months or possibly years earlier as would be the case for a cargo bay payload. In addition, the impact of on-orbit failures can often be minimized by a trained crew member.

Crew member duties for MACE will include assembly of the test article, test and checkout of sensors, actuators, and experiment support electronics, performing test runs, disassembly, and stowage for return to Earth. Performance of each of these functions by an astronaut represents significant simplification of experiment hardware over what would be required in a fully automated system. These functions can generally be performed by one astronaut unless video camera operation or other experiment observation tasks require additional personnel.

Involvement of the crew early in experiment design and development is highly recommended by both the Crew Integration and Payload Integration offices at NASA. Comments and suggestions made by experienced crew members early in the design process can often help avoid the significant time and expense of a redesign. Experiment operation can be optimized and astronaut interest generated and maintained.

3.1.3 Ease of Access to Orbital Environment

Middeck lockers provide relatively easy access to the orbiter manifest. Flight opportunities are available with a minimum wait. Middeck lockers are flown on every Shuttle flight, and are therefore not restricted to a particular mission/Shuttle configuration.

Spaceflight qualification and certification procedures and requirements are somewhat less stringent than those for payloads using the cargo bay. This is primarily due to the additional certification procedures required for payloads exposed to the space environment. Middeck payload certification requirements are discussed in section 3.2, and are in general simpler due to the "shirt sleeve" environment of the orbiter middeck.

3.1.4 Low Cost and Crew Risk

Costs associated with middeck locker payloads are lower than for other Shuttle payloads. This is easily seen when cargo bay payload development is considered. In addition to the qualification and certification costs discussed above, the experiment design would require full automation of assembly/deployment, test and checkout, operation, and stowage. While these costs are increasing, crew involvement is reduced to video or computer link monitoring. The cost and risks associated with EVA will most likely preclude the possibility of repair or modification of experiment hardware in the event of failure.

EVA with the test article affords some level of crew involvement as well as access to orbiter data downlink facilities, however the safety requirements and impact on other orbiter operations due to the required cabin depressurization and pre-breathe times will make this option very costly.

A final consideration is the ease with which a middeck locker payload can be reflown on subsequent flights. Any hardware or software which has been certified for spaceflight on the middeck can be re-flown without recertification. This greatly reduces the cost for follow-on experiments. Those changes which are required can be certified separately.

3.2 RESTRICTIONS ON PAYLOADS USING THE MIDDECK

The services described above are supplied with certain restrictions on payload utilization of orbiter resources. These are described below.

3.2.1 Payload Size and Weight

Each middeck locker provides 2 cubic feet of useable volume. It is not expected that MACE will require the use of stowage trays inside the lockers, permitting the experiment and mounting hardware to make full use of the available volume.

The maximum weight of all experiment and mounting hardware (including locker shell) and any protective provisions (foam inserts, etc,) is 70 pounds per single locker unit. The locker shell weighs approximately 16 pounds, leaving 54 pounds for the payload itself. Use of a single adapter plate permits mounting the payload directly to the forward bulkhead without a locker shell. The single adapter plate weighs 6.2 pounds, leaving 63.8 pounds for experiment hardware and protective provisions. Use of a double adapter plate (12.5 pounds), which permits use of two locker volumes without the standard locker shells, will leave 127.5 pounds for experiment hardware and protective provisions. It should be noted that 'payload supplied' shells must be spaceflight certified, thus use of the standard shells is preferred.

Overall middeck layout can be seen from Figures 3.2.1 and 3.2.2. Middeck dimensions in orbiter coordinates can be seen from Figure 3.2.3. Maximum width (Yo axis) is approximately 90". Maximum height (floor to ceiling) is approximately 80 ". Maximum depth overall (locker face to aft bulkhead) is approximately 88 ". Maximum depth (locker face to airlock hatch) is approximately 60".

Note that absolute values are not available, as mission specific hardware is often located on the middeck walls, etc. during flight.

The maximum size test article that can be easily accommodated in the middeck during experiment operations is approximately 76". This assumes the test article is oriented horizontally with respect to the middeck floor. It may be located either along the face of the forward lockers, or along the starboard side extending fore and aft. Negotiation with the NSTS is necessary to determine the extent to which other objects present in the middeck area on any given flight will reduce the maximum length allowable with a free floating test article.

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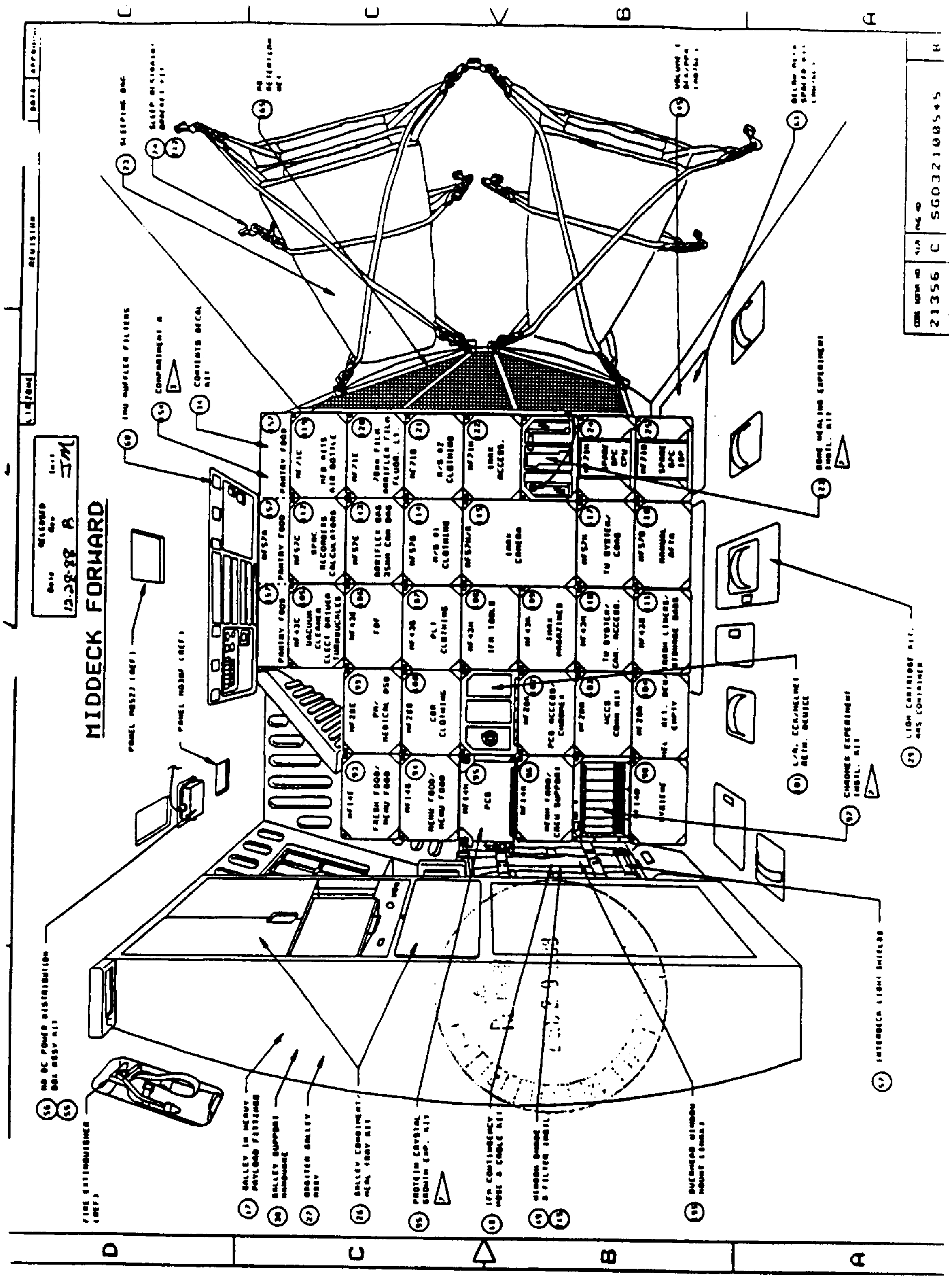

Figure 3.2.1 Middeck Forward View

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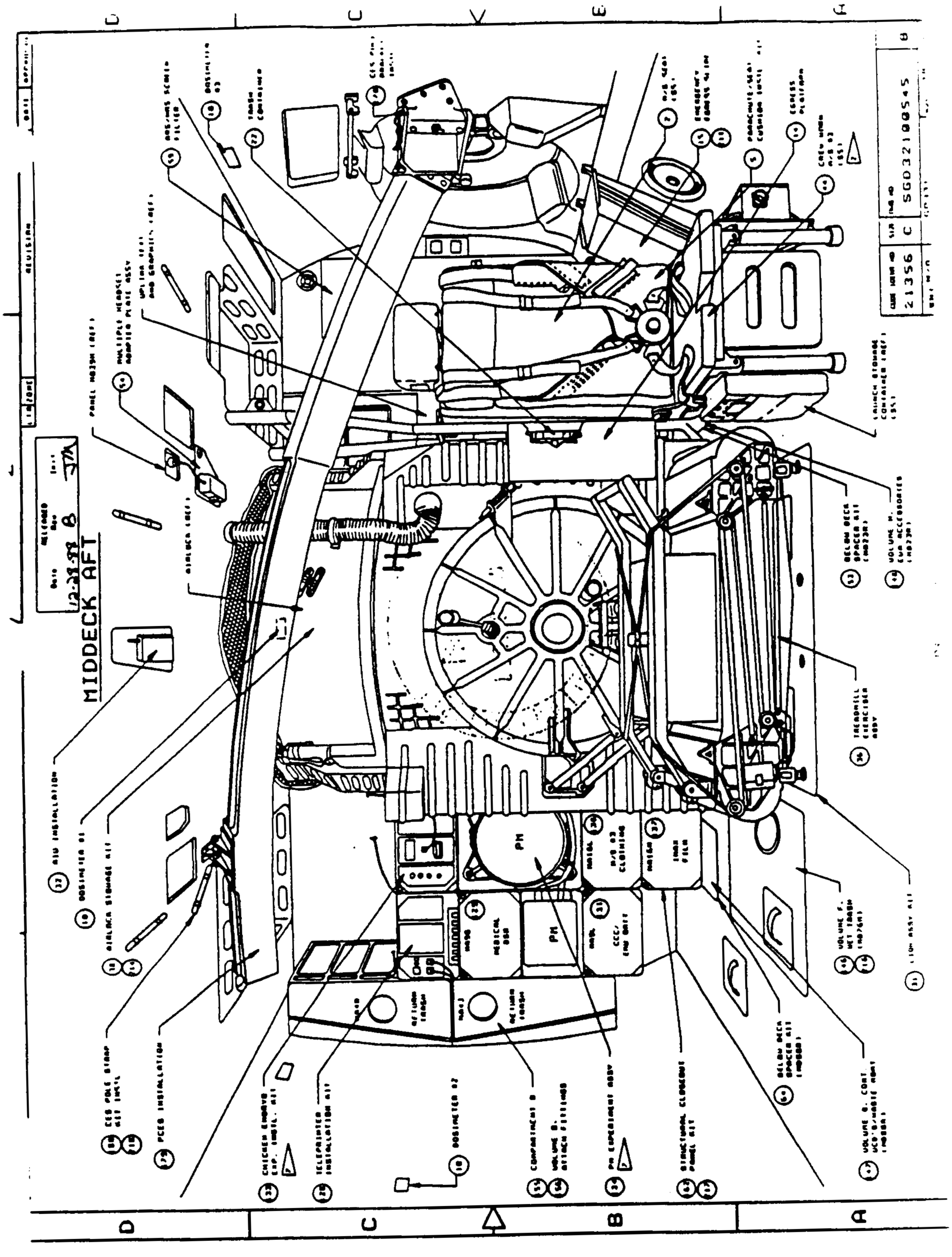


Figure 3.2.2 Middeck Aft View

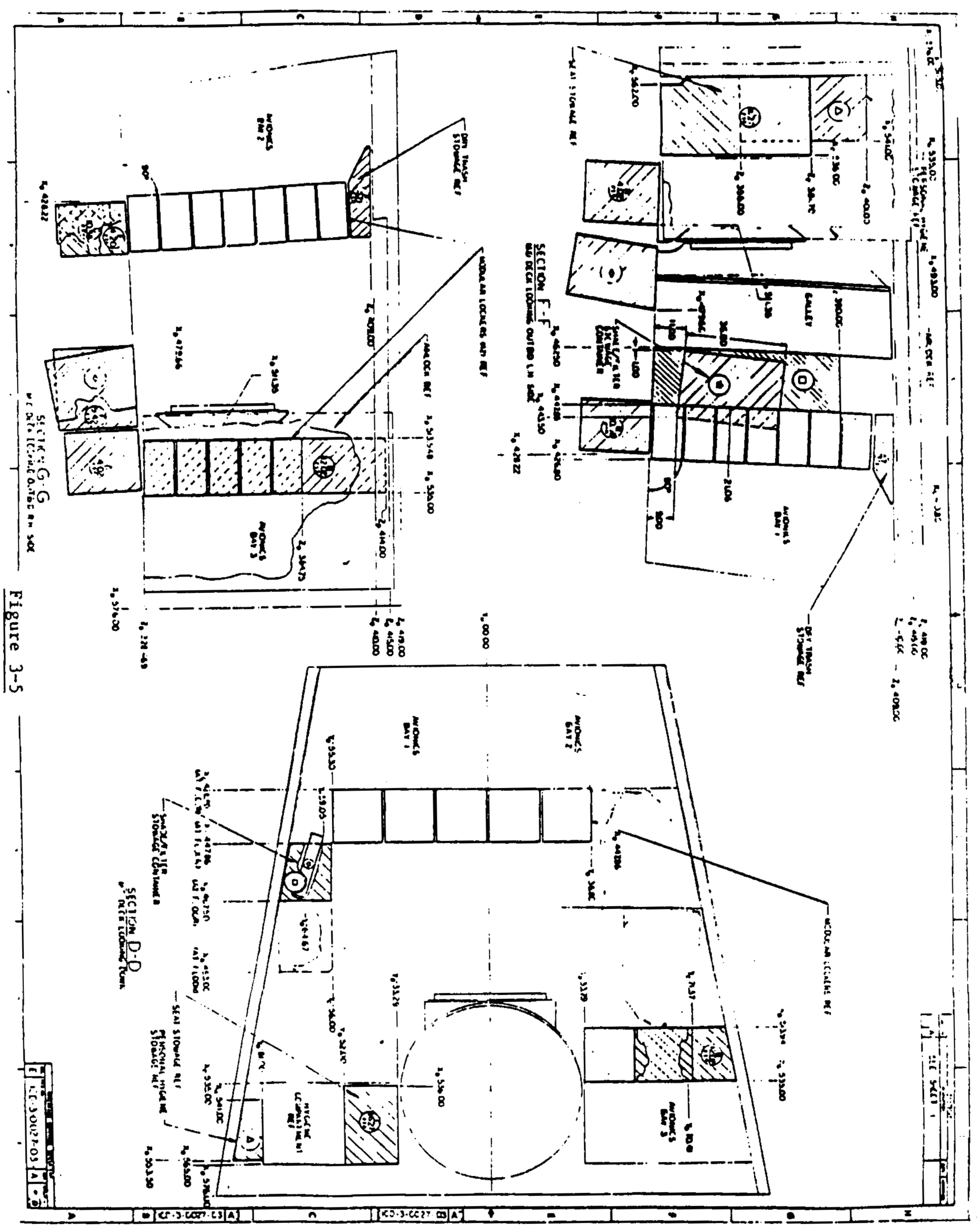


Figure 3.2.3 Middeck Layout (dimensions in Orbiter coordinates)

A test article 76" in length could be flown intact utilizing the Middeck Accommodations Rack (see section 3.3.3). If the MAR is not used, assembly of the test article on orbit is required, using a second middeck locker volume for stowage. It should be noted that safety requirements demand that a method to dismantle and stow the test article quickly (20 to 30 minutes) to allow crew egress during an emergency situation must be incorporated.

3.2.2 Power Consumption

The orbiter electrical system was not originally designed to power multiple middeck payloads. Thus, power use is strictly limited to 115 watts continuous DC per experiment for up to 8 hours. 200 watts peak DC power is permitted for periods of 10 seconds or less. Supply voltage is specified as +28 ± 4 VDC, and decreases with increasing power consumption. The minimum supply voltage versus power consumption is characterized in the IDD-MDK on page 7-2. This voltage curve must be taken into account in the design of all electronic systems.

Use of batteries is necessary for payloads requiring greater power than 115 W. It should be noted that the use of batteries poses safety concerns due to the potential for explosion, and their use will be carefully monitored. Heat dissipation must also remain within the limits discussed below, regardless of how much power is supplied by the orbiter.

3.2.3 Data Downlink Provisions

There are currently no provisions for data downlink from the orbiter middeck area. Data may be archived locally in the locker, with provisions made for crew interaction (see section 3.3.1, "Experiment Monitoring"). It is expected, however, that real time ground data analysis will be highly desirable for MACE. Therefore, a number of non-standard data downlink options were investigated.

- Data line to flight deck
- Biomedical data link
- Acoustic modem style communication via voice channel
- Data downlinked as video signal

Possible connection of MACE data output lines to the orbiter data systems was investigated. Interfacing payload computers with Shuttle data downlink systems is

standard for cargo bay payloads, however no provisions for access to these data systems exist on the middeck. Access could only be accomplished on the flight deck. The requirement for a length of cable to the flight deck, as well as the stringent certification procedures make this option costly. The cable poses safety problems for the crew, and could impact crew operations on the flight deck. The certification requirements stem from the fact that any computer system with access to orbiter data systems must not pose any threat to those systems.

A relatively low rate data system is sometimes used to downlink biomedical data from the crew. The second air-to-ground voice channel (AG 2) is used for this purpose. A third option investigated was to use AG 2 with a modem style interface. Preliminary talks with Payload Integration officials indicate that use of AG 2 in these ways, while not excluded, is generally not encouraged. As there are only two voice channels available, use of one would reduce the availability of the only backup. From the experiment perspective, downlink would be discontinued in the event of failure of AG 1.

The remaining option is to interface with the Shuttle video system. With the proper interface circuitry, the experiment could output a "standard" video signal, which could be fed to the orbiter video system through one of the connectors located at various places in the middeck ceiling. The bandwidth available in a video channel would allow 'dumping' large volumes of data in much shorter times than would be required for either of the voice channel options. For a slightly larger development cost, data could be mixed with a video camera output and downlinked in real time with a video picture. Costs for ground support equipment to accomplish retrieval of the data and video must be considered if this option is used.

3.2.4 Crew and Orbiter Safety

All payloads must be examined and approved through the Phase Safety Review Process. The MACE electronics package is not expected to pose any unusual hazards to crew or orbiter systems. However, free-floating of the test article will require that special attention be paid to the design of the test article from a safety point of view. Safety issues to be addressed include sharp edges on exposed surfaces, moving parts and their potential for injuring the crew, and the potential for the test article impacting other objects in the middeck.

The presence of an active closed loop control system and the potential for instability of a free floating test article requires that methods of shutdown be carefully considered. It

is desirable to incorporate three levels of safety: computer sensing and automatic shutdown, mechanical stops and microswitches to prevent test article motion beyond well defined limits, and an astronaut operated (manual) shutdown. Soft attachment to the orbiter structure (e.g. using elastic cords) might also be considered if free floating presents substantial safety problems.

The test article must be stowable for de-orbit in 20 to 30 minutes during contingency operations.

3.2.5 Payload and Shuttle Produced Vibration

Currently, there are no limitations specified for payload induced vibrations. It is recommended that this issue be pursued and documented through the Phase Safety Review process if the test article is attached to the locker structure. Preliminary discussions with NASA Payload Safety personnel have indicated that safety limit cut-offs would be sufficient to control for this hazard. Furthermore, the levels of force to be applied are low. Thus, payload induced vibrations will be small.

For a free floating test article, there are no vibration contamination considerations.

For a fixed test article, orbiter thruster firings will be a source of noise. Tables of accelerations due to primary and vernier RCS thruster firings are shown in Tables 3.2.1 and 3.2.2. These tables are given for motion about the vehicle center of rotation, located approximately at Xo = 1120, Yo = 0, Zo = 400 (orbiter coordinate system). The face of forward middeck locker MF 43H (roughly the center of the forward group of lockers) is located at approximately Xo = 447, Yo = -27, Zo = 363. All three angular accelerations may occur simultaneously.

The -ZLV attitude (cargo bay toward Earth) is the most common attitude, and in this configuration there is a mean time between thruster firings of approximately 5 minutes. Other attitudes require less frequent VRCS activity. The Gravity Gradient (GG) configuration (X axis parallel to gravity vector) requires no VRCS activity for long periods. It is not known how long the orbiter can remain in this attitude without thruster firings, but the time is estimated by Guidance and Navigation personnel as on the order of an orbit (90 minutes). GG attitude is used commonly for Detailed Technical Objectives (DTO's). Note that VRCS firing can be suppressed for periods of approximately 1 hour. This time can be negotiated with NSTS.

Table 3.2.1 Primary RCS Acceleration Levels (source: ICD-2-19001)

Acceleration	Command	Maximum Hi-Mode	Nominal Mode	Time Average
TRANSLATION (ft/sec^2)				
32 K Lbs Payload	+X	0.55*	0.27	0.29
	-X	N/A	-0.28	-0.27
	+Y	N/A	0.28	0.12
	-Y	N/A	-0.28	-0.15
	+Z	1.26**	0.42	0.43
	-Z	-0.94*	-0.55	-0.50
65 K Lbs Payload	+X	0.46*	0.23	0.24
	-X	N/A	-0.23	-0.22
	+Y	N/A	0.23	0.10
	-Y	N/A	-0.23	-0.12
	+Z	1.05**	0.35	0.35
	-Z	-0.80	-0.46	-0.42
ROTATION (deg/sec^2)				
32 K Lbs Payload	+Roll	N/A	1.09	0.80
	-Roll	N/A	-1.09	-0.89
	+Pitch	N/A	1.29	1.16
	-Pitch	N/A	-0.86	-0.81
	+Yaw	N/A	0.72	0.70
	-Yaw	N/A	-0.72	-0.62
65 K Lbs Payload	+Roll	N/A	1.03	0.76
	-Roll	N/A	-1.03	-0.84
	+Pitch	N/A	1.18	1.06
	-Pitch	N/A	-0.79	-0.74
	+Yaw	N/A	0.66	0.64
	-Yaw	N/A	-0.66	-0.57

* Hi-mode acceleration in +X and -Z is available only during OPS 1 (insertion) and OPS 3 (de-orbit) phases with TRANS DAP (Transition, digital autopilot).

** Hi-mode acceleration in +Z is available only during OPS 2 (on-orbit) phase with on-orbit DAP (digital autopilot).

Table 3.2.2 Vernier RCS Acceleration Levels (ICD-2-19001)

Payload	Rotation Command	Per Axis Rotational Acceleration deg/sec^2	Translational Crosscouple Acceleration, feet/second^2		
			X	Y	Z
32 K Lbs	+Pitch	0.0209	-0.0003	0.0	-0.0056
	-Pitch	-0.0163	0.0	0.0	-0.0077
	+Roll	0.0209	-0.0001	0.0027	-0.0067
	-Roll	-0.0209	-0.0001	-0.0027	-0.0067
	+Yaw	0.0175	-0.0001	-0.0011	-0.0029
	-Yaw	-0.0175	-0.0001	-0.0011	-0.0029
65 K Lbs	+Pitch	0.0191	-0.0002	0.0	-0.0047
	-Pitch	-0.0149	0.0	0.0	-0.0064
	+Roll	0.0196	-0.0001	0.0023	-0.0056
	-Roll	-0.0196	-0.0001	-0.0023	-0.0056
	+Yaw	0.0160	-0.0001	-0.0009	-0.0024
	-Yaw	-0.0160	-0.0001	-0.0009	-0.0024

Typical values for vibration of the middeck locker structure for various other noise sources are given below.

- Crew Motion : 10-4 to 10-3 g
- Fans, motors, etc. : 2 to 4 x 10-4 g
- Treadmill : 10-1 g

(source: JSC Payload Integration Office)

Thruster firing information is available post mission or with specialized ground support equipment during the mission. A time tag would be required on data recorded in the experiment for correlation with the thruster firing data.

If shuttle produced vibration must be minimized, scheduling of MACE activities can be made to coincide with "quiet" orbiter activities, (no thrusters firing, no crew exercise, etc.), as discussed in section 3.3.2 below.

3.2.6 Electromagnetic, Thermal, and Acoustic Noise Limits

The IDD-MDK is the controlling document for EMI, thermal, and acoustic contamination limits for middeck payloads. Standard payloads do not exceed the limits set forth in this document, however exceeding the recommended values does not automatically mean rejection for certification or flight assignment. Individual variances can be negotiated with the NSTS.

Note that the middeck does not provide for cooling of payloads except for venting into the crew compartment. The absence of gravity also means that convective cooling does not exist. Cooling fans must be provided if internal or external component temperatures exceed the values specified in the IDD-MDK.

3.2.7 Offgas and Flammability Requirements

Materials and components chosen for MACE must not release significant levels of toxic gasses into the crew compartment, or permit flames to propagate significant distances in the event of fire. Requirements are described in NASA Handbook 8060.1B, "Flammability, Odor, and Offgassing Requirements".

Applying these requirements to each experiment component under consideration would be difficult and time consuming. Therefore, the recommended approach for development and certification of the payload is for the hardware development team to select the systems, subsystems, and components in which they have the most experience and

which also have the highest expected success in fulfilling the experiment goals. Once the selections have been made, a design review process should be implemented to circumvent or identify to NSTS any components or elements that are not "standard" or require further evaluation and/or testing. In this way, the entire experiment package is evaluated for offgas and flammability at roughly the same time. This will ensure a high quality, custom experiment with the highest possible chance for success, while keeping certification costs at a minimum.

The main items in the certification process include the above mentioned off-gassing test and submission to NSTS of a list of all materials used in experiment components for flammability and toxicity analysis. Further tests may be required by NSTS, based on the results of this analysis. Further requirements for payload integration and certification are discussed in Section 5A, "Development, Certification, and Integration Plan".

3.2.8 Impact on Crew Activities

Although crew schedules are in general quite flexible, they are also quite demanding. The astronauts working day is generally limited to 8 hours, with time out for meals, etc. The primary scheduling concern will be the crew activities requirements of other payloads on the same flight. For example, a typical satellite deploy mission will not have any middeck activity on the first day, as the full crew is required for payload operations. While it is the responsibility of the NSTS to manifest compatible payloads, payload developers are encouraged to design their experiments with the goal of minimizing the potential for interference with other payloads. In the case of MACE, this could mean requiring provisions for access to other middeck lockers during experiment reset/reconfiguration periods, or securing the assembled test article safely during lunch or other middeck activity. Experiment run durations of 15 to 20 minutes are considered easy to accommodate, with time between runs for access to other lockers, etc.

Note that for Spacelab missions, it is presumed that the entire crew will be occupied for the duration of the workday, and will sleep in the middeck. Therefore, it should be negotiated with the NSTS that MACE not be manifested on a Spacelab flight.

3.3 SPECIAL SERVICES AND OPTIONS

Special services can be negotiated with the NSTS on a case by case basis. Services which might be of particular value to MACE have been outlined below.

3.3.1 Experiment Monitoring

In general, middeck experiments are monitored on the ground via a combination of NSTS provided video (one crew member required to operate the camera) and astronaut voice communication. Although many experiments store the video on tape for playback post-launch, it is expected that MACE will require on-orbit monitoring during experiment operations. This is easily accommodated by the NSTS, and can be negotiated in the Payload Integration Plan (PIP).

A GRiD 1530 is also available. This computer is a space qualified laptop PC compatible with a 3.5" floppy drive, 20 Mbyte hard disc, 8 Mbyte RAM, and Centronics parallel and RS-232 output ports. This unit is the backup for the standard crew computer, which is flown regularly as NSTS standard equipment. If use of the backup is desired, payload developers are responsible for its weight, power, and stowage volume. It can be used for payload monitoring, protocol updates, etc. One option for MACE would allow various experiment protocol options to be flown on discs with the ESM. On-orbit, in the event of unexpected system responses, new gain matrices, sequencing instructions, or other experiment parameters can be loaded from the GRiD.

3.3.2 Orbiter/Crew Quiet Time

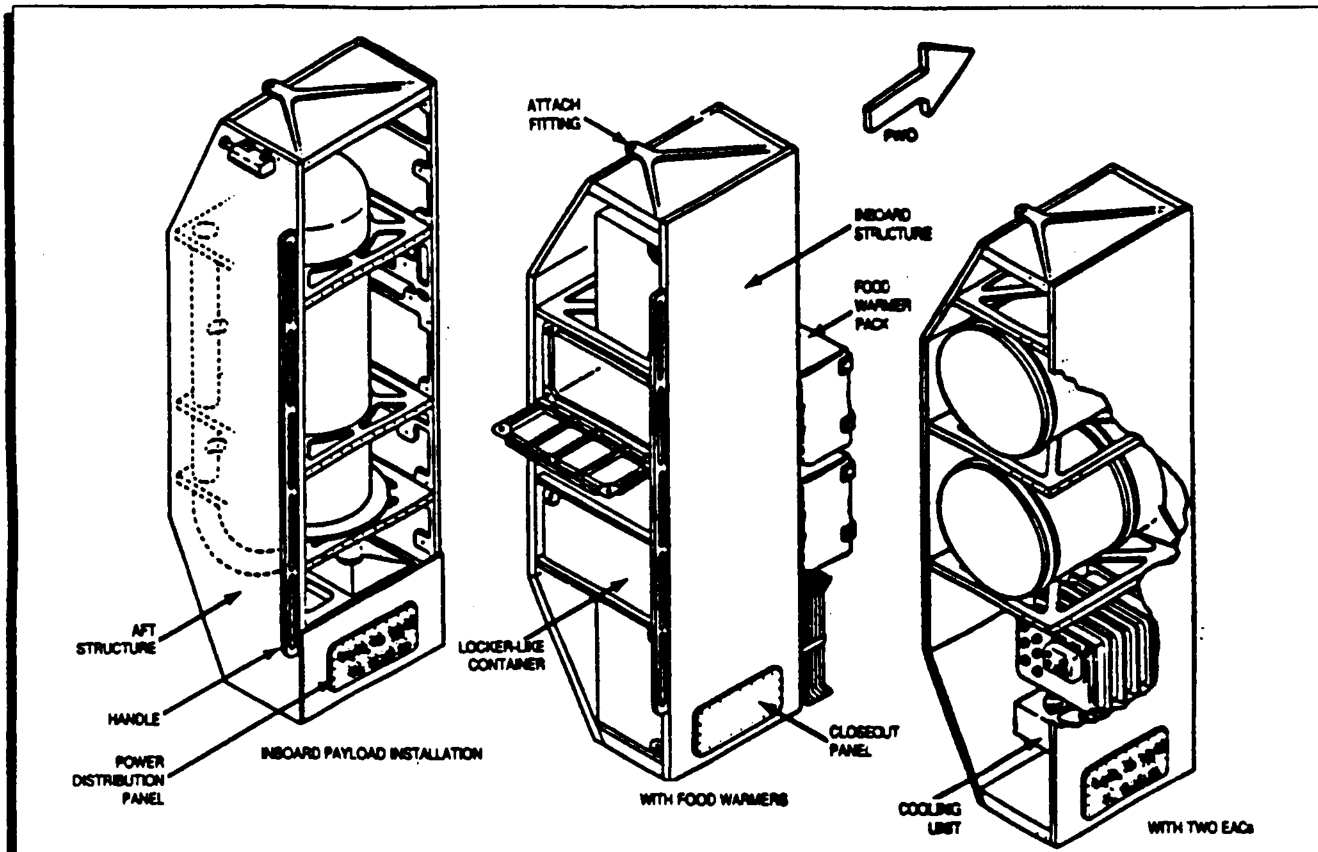
The payload developer may request from the NSTS that the crew minimize noisy activities such as using the treadmill, cabin movement, or operating motors and fans so as to minimize noise entering the experiment sensors. Durations of 20 to 30 minutes are seen as reasonable to request.

It may also be requested that the orbiter automatic RCS thruster firing be suppressed in order to maximize free-float time or minimize structural vibrations, as described in section 3.2.5. Discussions with Crew Integration representatives indicate that 1 hour is a likely maximum time limit for orbiter thruster suppression in typical vehicle attitudes. Note that secondary payloads are not permitted to require particular shuttle flight plans, however the gravity gradient attitude can be negotiated with the NSTS as "highly desirable".

3.3.3 Middeck Accommodations Rack

An additional volume called the Middeck Accommodations Rack (MAR) could be used to stow the test articles as well as the ESM (see Figure 3.3.1). Although still under development, the MAR would provide the equivalent of five middeck locker volumes. Up to 1000 Watts of power at either 28 VDC or 115 VAC will be available, along with an

Middeck Accommodations Rack (MAR)



Middeck Accommodations Rack

Importance

The MAR will increase the space available for small payloads and experiments in the middeck by supplementing the volume occupied by middeck stowage lockers.

Method

The MAR is designed as a versatile experiment integration facility with the equivalent stowage volume of five middeck stowage lockers. Experiment Apparatus Containers, trays, combinations thereof, or payloads specially sized to the MAR's capacity can be integrated in the carrier. Power distribution and active thermal control options are available to investigators using the MAR.

Orbiter Location

Middeck

Instrumentation

- Power Distribution Panel (optional)
- Active thermal control (optional)
- Active cooling options: circulated air, cooled water for coldplates, and cooled air
- Other instrumentation required, such as experiment control and data acquisition, must be provided with the experiment apparatus.

Data Acquisition

The MAR itself has no data acquisition capabilities. Data are acquired through instrumentation provided with the experiment apparatus contained in the MAR or by other supporting instrumentation.

active thermal control system. Maximum payload weight would be 157.5 pounds. Dimensions are approximately (LxWxH) 22"x 21"x 79". Thus a test article of 76" in length could be stowed with a minimum of assembly/disassembly required. It is recommended that the development of the MAR be closely monitored for potential utilization by MACE.

3.3.4 Free Floating Test Article

MACE design includes the possibility of free-floating the test article in the middeck area. This provides isolation from structural noise associated with the orbiter, and a more realistic simulation of the orbital environment.

Free float time would be limited to several minutes by test article size, ventilation air flow rates, residual gravity, and orbiter drag. The size of the crew, the duration of test runs, and other hardware in the middeck will in turn limit test article size. Payload Integration personnel have indicated that free floating would require more stringent safety procedures, but could be accommodated.

3.3.5 Use of Airlock

Also investigated was the possible use of the airlock for execution of experiment objectives. Free floating the test article in this location would provide isolation from middeck acoustic noise, atmospheric damping, and ventilation air flows. Depressurization of the airlock would provide the most accurate simulation of the orbital environment, without actually requiring EVA or cargo bay operation.

It was found, however, that the certification requirements associated with exposing a payload element to the space environment and returning it to the middeck would be expensive. Conversations with NSTS managers at JSC have indicated that the use of the airlock for experimental purposes is highly irregular. The certification process would also be irregular and complex in contrast to using the middeck only. In addition, the airlock cannot be depressurized from the middeck. A suited crew member is required to be inside the airlock during depressurization. This would require lowering the orbiter cabin pressure to 10.2 psi for 8 hours prior to depressurization, and would also require pre-breathe time for the astronaut. Further, there are no provisions for data transfer from the airlock to the middeck. Lastly, it is not likely that use of the airlock during a mission which required EVA would be permitted, as stowage of the three pressure suits (two for EVA, one for contingency) during experiment operations would heavily impact other operations on the middeck.

For these reasons it is recommended that if use of the airlock is pursued, it remain pressurized with the hatch partially open to permit umbilical cable travel to the ESM, located in a middeck locker. This approach would not have the benefit of experiment operation in vacuum, but would be much more easily integrated and certified, and thus would be less costly.

Chapter Four: Detailed Design of the Multibody Test Article

4.1 INTRODUCTION

As a result of the criteria developed in Chapter 2, the multibody test article has been selected as the reference test article. The rationale for choosing this as the reference can be summarized as follows:

1. *Gravity effects* The modification of the joint behavior, as well as the gravity effects on the stiffness/modes make on-orbit testing desirable.
2. *Suspension effects.* The three dimensional structural behavior of multibody platforms make suspension systems complicate and substantially limit ground tests.
3. *Independent control systems.* Various payloads are structurally coupled through a flexible bus
4. *Relevancy.* Multibody platforms are part of NASA's near term programs (Space Station Polar Platform)
5. *Flexibility.* Can incorporate various types of payloads/disturbances, including fluid slosh, spinning, and slewing. Can also incorporate "precision" aspects such as interferometry (by mounting a laser on the bus) and robotics (by mounting a flexible manipulator on the bus).

As was shown in Chapter 2, this test article clearly fits in the *development* category. In addition, the on-orbit experiment allows procedures to be be developed for the remote debugging, testing and fine tuning of flexible, articulated systems inside the STS middeck.

In this section, a candidate multibody test article will be described in detail. The various payloads and disturbances which can be attached to the test article will be listed, and an initial configuration for the test article will be presented, along with a preliminary sizing of the on-orbit computer requirements. In addition, follow-on configurations which may be tested on subsequent flights will be presented.

4.2 MULTIBODY ISSUES

4.2.1 Payloads and Disturbances

A review of recent Proceedings of the Workshop on Multibody Simulation held in April, 1988 at the Jet Propulsion Laboratory identified three different types of payloads which a multibody platform may support:

- *Pointing*. Payloads which have to maintain their orientation with respect to a point located off the multibody platform
- *Tracking or scanning*. Payloads which follow a predetermined angular profile, usually to observe a section of space or of a planet surface.
- *Articulating*. Flexible manipulators attached to a platform to perform automated servicing tasks.

The types of disturbances which a multibody satellite might be subjected to, in addition to any disturbances arising from the three types of payloads listed above, include,

- *Spinning bodies*. Arising from rotating machinery mounted on the bus structure or on a payload.
- *Fluid slosh*. This disturbance is due to the presence of maneuvering fuel on board the spacecraft.
- *Slow slewing maneuvers*. From solar panels, solar dynamic units, or other similar articulated flexible appendages.
- *Periodic and Random disturbances*. From machinery or the space environment such as micrometeor impacts.

Given the time constraints imposed by the STS middeck testing environment, it is unlikely that all seven disturbance/payloads can be tested during a single flight. For this reason, it became clear very early in the program that the most efficient test article design would be one which would permit various payloads and disturbances to be attached and removed, depending on the goal of the particular experiment that is carried out. A reconfigurable, truss-like multi-flight test article was selected for this purpose and will be described in Section 4.3. First, however, the various types of tests that can be carried out on a multibody platform will be listed. These were also obtained by reviewing the previously mentioned Multibody Simulation Proceedings.

4.2.2 Tests

The primary objective of the multibody platform is to achieve accommodation of multiple interacting payloads with varying and independent control objectives, mounted on a structure with time varying dynamics. Even though in general precision pointing and tracking requirements are not stringent, there is a desire to attenuate structure borne noise due to the disturbances arising from other payloads. To this end, some of the tests that may be carried out include:

- Measurement of pointing accuracy of various experiments.
- Jitter suppression of tracking and pointing devices.
- Vibration isolation using both payload-mounted and bus-mounted actuators and sensors.
- Minimization of settling times.
- Shaping of commanded input profiles to achieve minimum excitation of flexible modes.
- Modelling of on-orbit fluid-structure interaction.
- Deployment dynamics and control.

In addition, the multipayload test article can be used to verify some purely structural dynamic issues, such as disturbance modelling, and nonlinear modelling of large motion, flexible modes.

Having identified the various types of payloads and disturbances, as well as the possible tests that can be carried out on a multibody platform, it is now possible to proceed with the design of the reference MACE test article.

4.3 TEST ARTICLE DESIGN

As mentioned in the previous section, the concept of an multi-flight test article in which numerous combinations of performance payloads and disturbances can be attached is very appealing, given the large number of devices and disturbances that can be present on a multibody platform, along with the time constraints imposed by the STS middeck. With this in mind, the initial configuration of such a test article is shown in Fig. 4.3.1. It consists of a segmented straight tubular bus with two tracking/pointing payloads at each end. An active segment utilizing piezoelectric actuators to induce bending in the structure is

located in the center of the bus. This configuration is referred to as the Reference Multibody Test Article (RMTA).

A segmented tubular design was chosen as the support bus structure for the following reasons. First, such a structure lends itself easily to the evolutionary test article concept since it is reasonably straightforward to modify its geometry by attaching more tubular sections at angles to each other in order to achieve a structure of varying geometry. It is also possible to incorporate active elements such as piezoelectric tubular members into some of the sections which can be used in achieving a control objective. Through the use of a universal sleeve joint the segmented tubular design allows for numerous attachment points for other active elements such as PMAs, torque wheels, or accelerometers. Finally, it is simpler to assemble and deploy than a truss structure of equal length, and the vibrational frequencies would be lower for a given mass, thus reducing the bandwidth required on the control computer and more closely approximating proposed future space structures. In addition, buckling of individual members under normal excitation conditions of a truss structure sized to fit in the middeck leads to the design of trusses with cross-sections of two to three inches in width. Not only would such a structure be difficult to manufacture, but in addition its dynamic behavior will, to any significant accuracy, be that of a continuous beam. For these reasons, it was felt unnecessary to increase the cost and complexity of the proposed test article and the tubular design was selected.

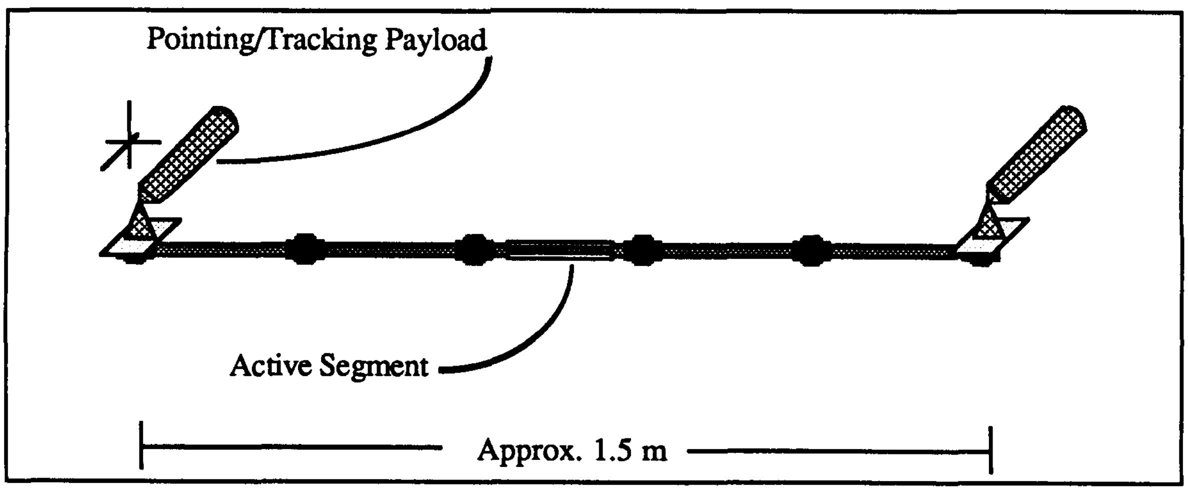


Figure 4.3.1 Initial configuration for multibody payload test article

In order to fit into the middeck area in its fully extended position, the maximum length allowed for the tube is approximately 1.5 m. Since it is desirable to be able to articulate the structure at various points along its length as the test article evolves, it is

necessary to keep the individual segment lengths short enough to allow two articulations to be present in the structure. A segment length of 0.30 m would require 5 segments to complete the fully extended tubular structure.

The bending frequencies for the reference test article are shown in Fig. 4.3.2. These frequencies were obtained using a finite element model assuming a 2kg payload on each end, a 3/4" diameter aluminum tubular bus with 1/8" wall thickness. In order to lower the natural frequencies of the structure, distributed mass was added to the model uniformally. Each curve in the figure corresponds to different amounts of distributed mass. Note that for a total weight of 16.7 kg, there are over 8 structural bending modes located below 100 Hz, with the first two fundamental bending frequencies located below 10 Hz. In addition, of course, there are the articulation modes of the payloads, and the rigid body modes of the entire assembly. A more detailed open-loop modelling of the proposed test article will be undertaken as part of the Phase B effort.

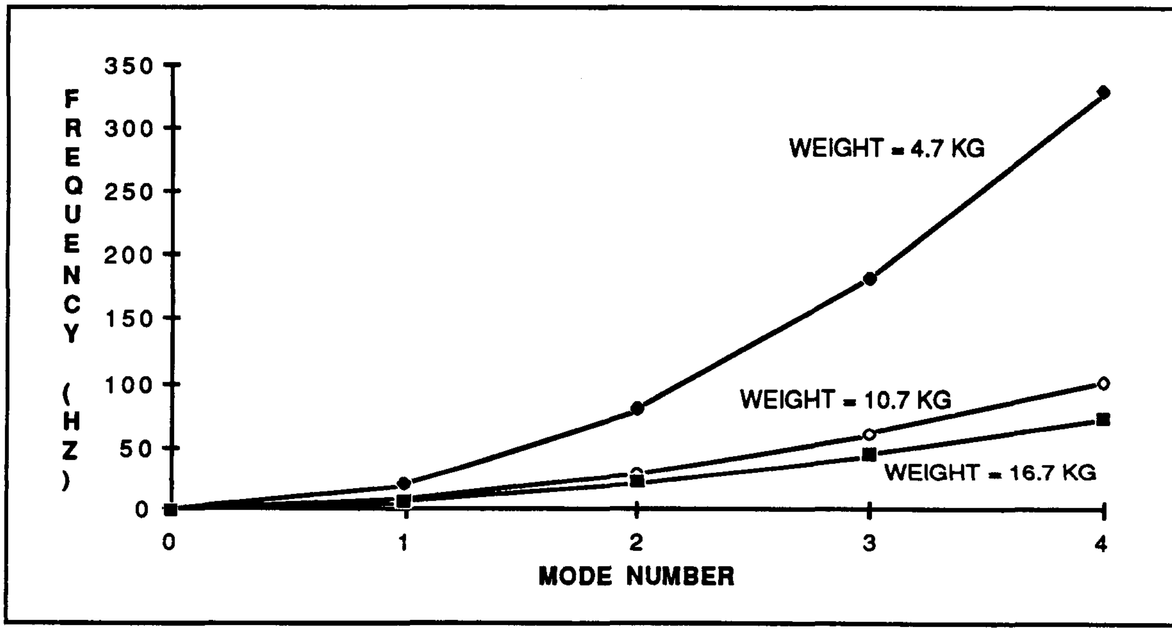


Figure 4.3.2 **Frequencies of reference multibody platform for various distributed weights. Each point represents two (in plane and out of plane) elastic bending modes.**

Three different types of building block elements are required:

- *The passive tubular segment.* This consists simply of aluminum or composite tube with a sleeve attachment to connect to the universal joints. No instrumentation or actuation devices are present, but there is an internal cabling feed-through connection to provide continuity in the instrumentation and

actuation signal cables from other building block elements. The cables run along the inside of the tubes.

- *The active tubular segment.* This is an active tube manufactured using piezoelectric or other similar strain inducing material, as well as a protective outer shell made from glass or graphite/epoxy materials. As in the passive segments, wiring runs along an inner shell inside the tubes. The center core of the tubes is hollow. This element is not simply an actuator, since it will be capable of carrying passive loads.
- *The joints.* These elements serve two purposes: they provide the interconnection between the various tubular segments of the structure and also provide attachment points for the various payloads that are to be attached to the structure. The attachment can be done through grooved/sleeve connectors, or other quick connect joint design. The joint has instrumentation wiring interface connectors to provide electrical continuity between the attached tubular segments, as well as to provide data channels to permit the sensors and actuators unique to the various payloads to communicate with the system computer. Unused joint ports would have electrical termination caps attached.

The exact number of data channels available in each bay will be discussed in the following section.

4.3.1 Instrumentation and Actuation

PASSIVE TUBULAR SEGMENT The passive segment contains no instrumentation or actuation and only provides electrical continuity through a pair of instrumentation wiring interfaces at each end.

ACTIVE TUBULAR SEGMENT Each active segment contains a set of piezoelectric (or other similar material) actuators. The actuators will provide control over bending in the structure in both vibrational planes. Strain gauges or other similar devices will be used for strain measurement. Therefore, each active active tubular segment will require 2 D/A channels and 2 to 4 A/D channels.

JOINTS The joints themselves will have no instrumentation or actuation. However, they will provide interface with the various payload attachments. Each payload will have available to it 2 D/A and 6 A/D channels for the use of the payload or disturbance device that will be mounted on it, along with power and ground lines. These channels will be available to connect the payload to the computer, and therefore allows each payload to have

up to 2 actuators and 4 sensors unique to its mission. In addition, the joint provides connections for two inertial actuator devices, such as proof mass actuators or reaction torque wheels. A total of 2 D/A and 4 A/D channels are available for this purpose.

PAYLOADS Each pointing/tracking payload has a two axis motor/gimbal actuator on which a angular rate gyroscope triax is mounted. In addition, tachometers and potentiometers would measure the relative angular rate and displacement of the payloads. This requires a total of 2 D/A and 6 A/D channels per payload, since only two channels would be required from the gyro triax. This is the same number of channels that is provided by the joint interface to each payload.

ADDITIONAL SENSORS/ACTUATORS At this time, the reference design does not have additional sensors and actuators. However, due to the interface available at the joints, strain gauges or proof mass actuators could easily be incorporated, if ground testing rand numerical modelling reveals the need for additional measurement/actuation. A conservative estimate would be that an additional 2 actuators may be placed along the structure,

4.3.2 Computers

For the reference configuration shown in Fig. 4.3.1, there is a maximum of 8 actuator commands and 16 measurements. This assumes 2 additional actuators, in addition to those on the payloads and in the active tubular segment, have been placed along the structure. A simple finite element analysis of the structure reveals at least 20 beam bending modes below 350 Hz. In addition, there are 12 rigid body modes, four to six torsion modes, and eight articulation modes. This gives a total of 46 modes. Assuming a 6.6 MFlop computer (SCI Computer or Sandac computer), this gives a maximum sampling frequency of

output feedback: 17 kHz
general form (with estimator): 620 Hz
input canonical form: 4100 Hz

These numbers assume a 30% overhead for conversion and a 30% overhead for housekeeping by the computer. Except for the general form, the maximum sampling frequencies are well above the Nyquist frequency of 700 Hz. There are, of course, particular issues associated with each type of feedback formulation, but the numbers above do show that for a presently available computer, the required sampling frequencies are feasible. A detailed discussion of the available computer for the MACE program is given in

Section 4.5. The computation method used in obtaining the above frequencies is given in Appendix E.

4.4 EXPERIMENTAL DESIGN

The MACE experiment provides a testbed in the shuttle middeck for studying the interaction of automatic control systems with dynamic space structures in ways which are not feasible in the earth-bound 1-g environment. As discussed in Chapter 2 (Test Article Options), the fundamental goal of the multibody test article is to develop technology to permit multiple payloads to effectively perform their various missions mounted together on a single support structure.

The primary experiment element consists of a model multibody space structure (the **multibody test article**) with controlled moving elements such as tracking antennae (the **test article payloads**). The test article is acted upon by both a control signal for carrying out its task (the **performance stimulus**) and an interfering signal (the **disturbance stimulus**). Both signals act on the test article through a set of one or more motors and shakers (the **actuators**). A series of accelerometers, rate gyros, and force transducers (the **sensors**) are used to measure the dynamic state of the test article. Signals derived from the sensors are fed to a high speed digital computer on which candidate automatic control algorithms are implemented (the **feedback control**). The feedback control generates control signals to the actuators to maximize the performance of the test article elements. The sensor signals are also sent to a mass storage device where they are stored for later analysis (the **measurements**). The performance and disturbance signals as well as information on the state of the feedback control algorithms are also stored as part of the measurement set.

Although many of the abovementioned factors could be varied in a systematic way as part of the experiment, the first flight of MACE will concentrate on examining the performance of a controlled payload performing pointing and tracking tasks on the multibody platform. The payload will carry out its pointing or tracking task in the presence of disturbances on the multibody platform due to either (1) another controlled payload or (2) random vibration applied to the performance payload, to a second payload, or to the multibody platform (via the active member). Performance will be measured using a performance metric derived from the measurements. Disturbances will be restricted to: slewing, pointing, and tracking of the second payload or random vibrations of either

payload or the active member. The characteristics of the the feedback control, actuators, and sensors will be chosen to best accomplish these experiment goals.

The experiment will consist of three series of test runs:

1. Pointing performance in the presence of slewing or random vibration
2. Tracking performance in the presence of slewing or random vibration
3. Pointing or tracking performance in the presence of a second payload performing its own pointing or tracking task.

For each experiment run, performance will be measured in the presence of a specific disturbance:

1. Random vibration
2. Planar slewing maneuvers
3. Non-planar slewing maneuvers.

For series 3 these disturbances will be combined with the tracking task on the second payload. The characteristics and ranges of both the performance and disturbance stimuli will be determined as part of the MACE phase B development effort. Table 4.4.1 summarizes the tests in three series as currently envisioned. The issues to be addressed in each category are addressed briefly in the following paragraphs.

POINTING The mission of this payload will be accomplished using a three-axis rotational gyro package mounted on a motor/gimbal. The motor arrangement will be capable of both planar and non-planar motion. The mass of this device will be a substantial fraction of the mass of the total structure, in order to truly have a multi-body system with time-varying dynamics.

The goal of this device would be to keep the sensor package from moving angularly from some pre-set inertial angular position. Lateral motion of the payload will not be sensed and therefore will not be controlled.

Issues that need to be addressed during the phase B development effort include:

1. The accuracy level that can be maintained using the gyro package
2. The level of disturbance that is transmitted to the support structure by the motors

Table 4.4.1 Proposed closed-loop test series for Reference Multibody Test Article

Test	Left Disturbance or Performance Metric	Right Disturbance or Performance Metric	Issues Addressed
1			All test in series 1 address disturbance rejection, jitter suppression and pointing performance
1a)	Pointing	Random	Pointing performance in presence of random vibration
1b)	Pointing	Small Angle, Planar Slew	Pointing performance in presence of small slewing maneuvers at various rates.
1c)	Pointing	Large Angle, Planar Slew	Pointing performance in presence of large slewing maneuvers at various rates, time varying dynamics of structure.
1d)	Pointing	Small Angle, Non-Plan. Slew	Pointing performance in presence of large slewing maneuvers at various rates, three dimensional structural motion
1e)	Pointing	Large Angle, Non-Plan. Slew	Pointing performance in presence of large slewing maneuvers at various rates, three dimensional structural motion, time varying dynamics of structure.
2			All test in series 2 address disturbance rejection, jitter suppression and tracking performance
2a)	Tracking	Random	Tracking performance in presence of random vibration
2b)	Tracking	Small Angle, Planar Slew	Tracking performance in presence of small slewing maneuvers at various rates.
2c)	Tracking	Large Angle, Planar Slew	Tracking performance in presence of large slewing maneuvers at various rates, time varying dynamics of structure.
2d)	Tracking	Small Angle, Non-Plan. Slew	Tracking performance in presence of large slewing maneuvers at various rates, three dimensional structural motion.
2e)	Tracking	Large Angle, Non-Plan. Slew	Tracking performance in presence of large slewing maneuvers at various rates, three dimensional structural motion, time varying dynamics of structure
3			All test in series 3 address disturbance rejection, jitter suppression and tracking and pointing performance
3a)	Pointing	Planar Tracking, Small Angle	Simultaneous pointing and tracking performance: multiple control system interaction.
3b)	Pointing	Planar Tracking, Large Angle	Simultaneous pointing and tracking performance: multiple control system interaction,.time varying dynamics of structure.
3c)	Pointing	Non-Planar Tracking, Small Angle	Simultaneous pointing and tracking performance: multiple control system interaction,.three dimensional structural motion.
3c)	Pointing	Non-Planar Tracking, Large Angle	Simultaneous pointing and tracking performance: multiple control system interaction,.three dimensional structural motion, time varying dynamics of structure.

3. The development of algorithms to perform the actual pointing control of the payload.

TRACKING The same device used to fulfil the pointing mission can be used in investigating how a tracking device is affected by structure borne disturbance and multibody, time varying dynamics. The motor/gimbal mount can be preprogrammed to carry out a torque profile. Performance could be measured either off-line by checking the actual tracking profile with the desired one, or using the angular rate information to modify the tracking profile during the test.

Issues that need to be addressed during the phase B development effort include:

1. Determination of the tracking profile
2. Determination of the tracking rate or rates
3. Determination of whether off-line determination of performance is adequate or if real-time measurement of the angular rates is required.

SLEWING The same payload that is used to perform the tracking and pointing missions will be used to impart a disturbance arising from the slewing of a structure on the multibody platform. In fact, the slewing disturbance can be thought of as simply a racking motion where there is no feedback to establish whether the tracking profile was accomplished as desired.

Issues that need to be addressed during the phase B development effort include:

1. Angular range of the slewing motion
2. Rate of the slewing motion
3. Desirability of performing non-planar motions.

RANDOM Random disturbances will be applied to the structure using either the pointing/tracking payload, the active member, or an attached proof mass actuator. These disturbances will be applied in the first two series of tests because, coupled with a pointing or tracking payload, they are the simplest tests that can be performed on the structure and can serve to familiarize the crew with the experiment as well as to identify possible problems with the hardware once in orbit.

Issues that need to be addressed during the phase B development effort include:

1. Amplitude and frequency content of the random signal.

2. Selection of actuator to input the random signal to the structure.

The test series explained above are listed in Table 4.4.1. It is expected that these tests will require two full on-orbit astronaut days. However, it is possible that additional time may be available. In the next section, possible additional tests and structural configurations will be presented.

4.4.1 Subsequent tests and evolutionary test articles

If additional on-orbit time becomes available, either due to STS scheduling concerns or if the proposed test series is accomplished more rapidly than expected, additional tests could be carried out. A more precise estimate of the amount of on-orbit experiment time required will be obtained during the Phase B/C ground test program. Additional tests may include:

- **Flexible payload.** The reference design does not allow for flexibility in the two pointing/tracking payloads. Adding a flexible member to the payload could be accomplished and a subset of the tests presented in Table 4.4.1 could be performed to examine how the flexibility of the payload affects the performance and stability.
- **Bending/torsion coupled structure.** The reference design can be modified, as shown in Fig. 4.4.1 and 4.4.2 to provide a more complex structure on which to perform the active control.

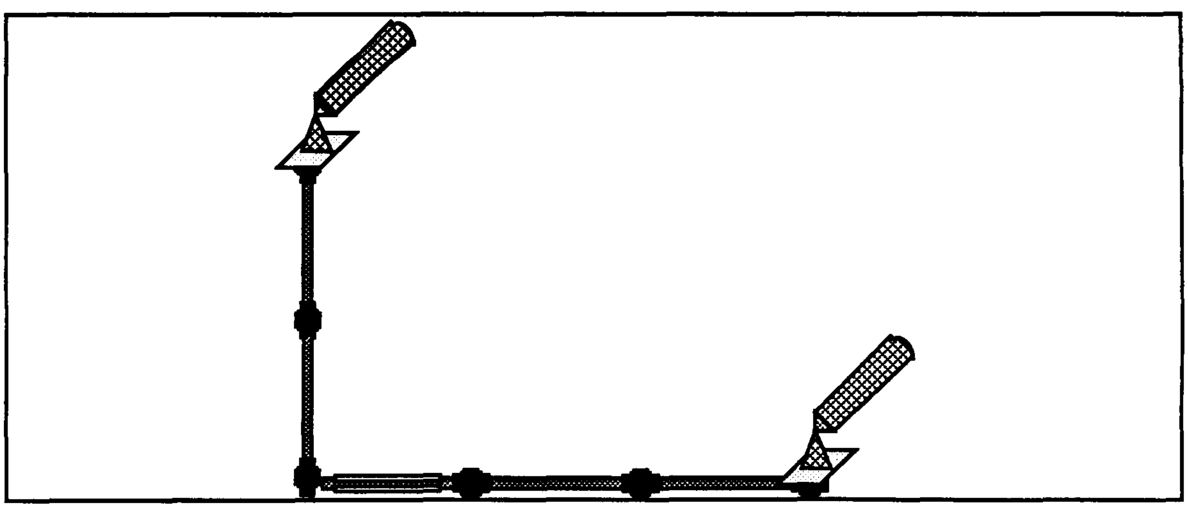


Figure 4.4.1 Bending/Torsion coupled structure with two pointing/tracking payloads

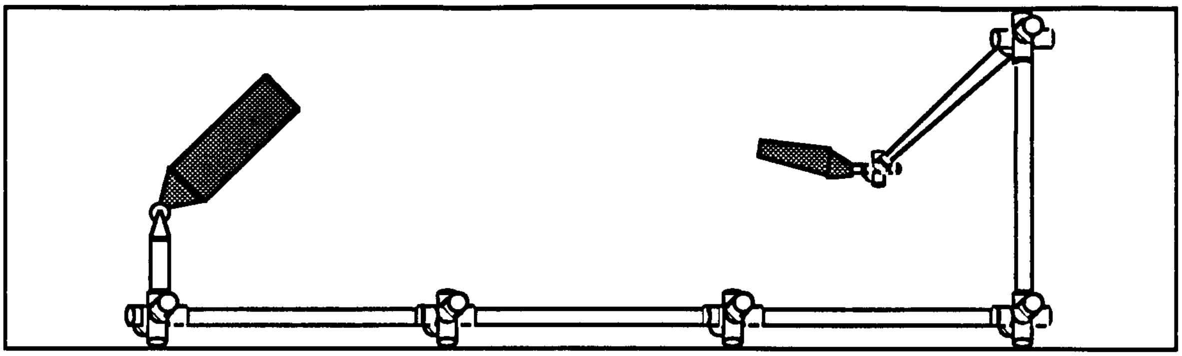


Figure 4.4.2 Three dimensional structure with two pointing/tracking payloads

- **Two point alignment.** Interest has been expressed by the Jet Propulsion Laboratory to modify the refernece multibody test article in order to conduct an interferometric-type test. Their proposed configuration is shown in Fig. 4.4.3 It consists of a laser ranging system mounted on either end of the bus structure with an active bay mounted at the joint. This active bay consists of extensional piezoelectric strut members arranged to actuate bending in the structure. Alternatively, it would be possible to perform a similar, but simpler, experiment using the straight tubular configuration with a laser and target mounted at the ends of the structure (Fig. 4.4.4). JPL may supply some of the additional hardware required for this configurations. For more detail, see Appendix B on interferometric test articles. Testing of these articles would need to be closely coupled to both the MIT SERC proposed interferometric test-bed and the JPL Interferometer Focus Mission Instrument Testbed program in order to assure a valuable scientific return on the flight which could not be obtained on earth.

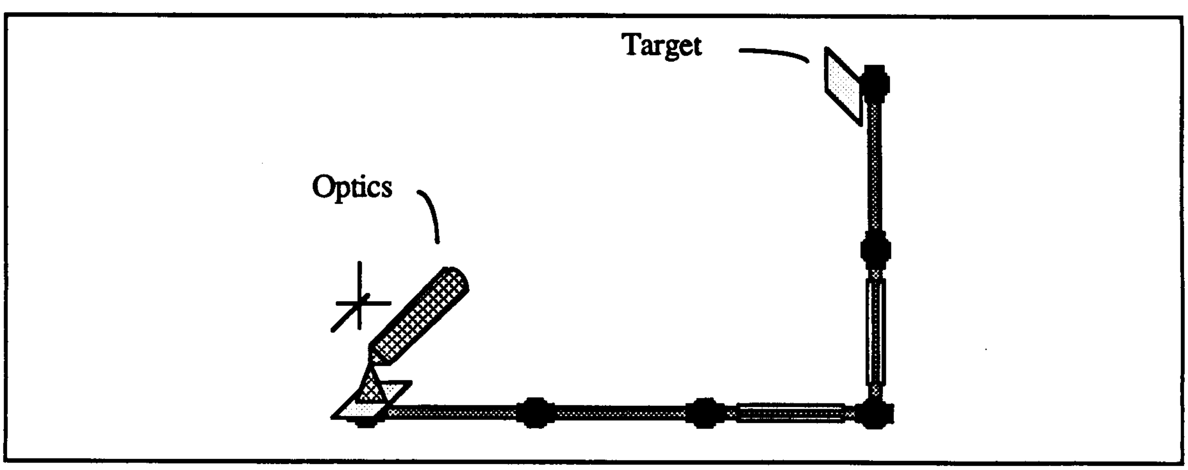


Figure 4.4.3 Two point alignment follow-on experiment.

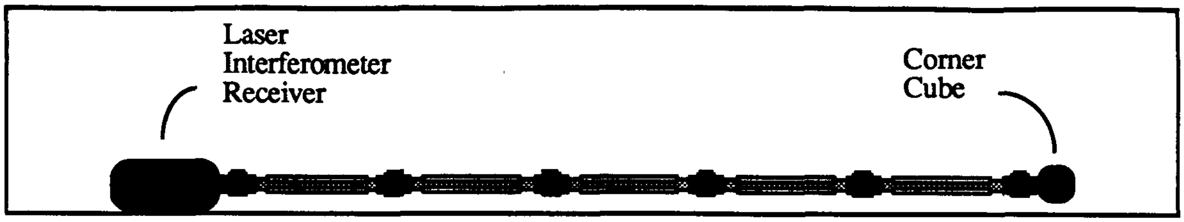


Figure 4.4.4 Test article configuration for precision alignment experiments typical of interferometry.

- **Passive damping.** Members with passive damping material such as viscoelastic could be substituted for any one of the tubular members of the structure. Alternatively, passive damping devices such as proof mass dampers, could be attached to the joints.
- **Joint slop.** This could be investigated by simply loosening the sleeve joint at any one of the interface locations along the structure.

All of these tests could obviously not be carried out on a single flight. This is why the tests in Table 4.4.1 refer to only the refernece configuration shown in Fig. 4.3.1. However, due to the modularity of the test article design, very little hardware modification is required from the RMTA to perform any of the additional tests listed above. The passive tubular segments can be assembled in straight or angular configurations without any additional hardware. A flexible attachment would need to be flown to test a flexible payload and a laser metrology system would be requried for either of the interferometric configuration. It is therefore conceivable to fly the small amount of additional hardware required for these tests and to perform them as time permits. Of course, the MACE objective is to develop a structural control testing facility, and therefore it would be available for use on subsequent flights. It is expected that as part of the ground test program of Phases B/C, a better formulation of the testing difficulties and time requirements will be obtained, leading to a more detailed breakdown and selection of the on-orbit tests.

4.4.2 Flight Operations

The primary tests and their scientific objectives have been outlined in Section 4.4 and are summarized in Table 4.4.1. In addition to these flight operations, there are additional procedures that will need to be carried out.

The first task that will need to be performed by the mission specialist is the unstowage and assembly of the test article and connection of the data/power umbilical to the locker containing the experimental support module. This procedure will require

approximately 20 to 30 minutes. This will be followed by an automated diagnostic routine to verify the status of the electronics and other equipment.

Before conducting the closed-loop tests, the astronaut will perform an open-loop identification routine consisting of either sine-sweeps or random excitation inputs to the test article to obtain an experimental open-loop model for the structure. This will be compared to the ground models and analytical predictions. If necessary, the control algorithms will be modified to take into account any variations in the open-loop model. These open-loop tests can take between 30 and 60 minutes.

After the open-loop identification tests, the closed-loop testing will commence. The three test series listed in Table 4.4.1 will be performed. It is expected that each test of the series will take no longer than 15 minutes each. However, each test may be run multiple times in order to obtain measures of performance of various algorithms.

Testing can be interrupted at any point. There is no requirement to complete a series of tests during a continuous time period. At the end of the testing period, the article may be disassembled and restowed or, if possible, may be placed in its assemble configuration out of the way of the astronauts.

Procedures for the second day of testing will parallel those already described. Open-loop testing will not be required unless some unforeseen even has occurred in the interim between tests that may have modified the plant dynamics. At the end of the test day, the structure will be disassembled and restowed for landing. Disassembly will take no longer than 30 minutes.

Two points need to be stressed in this testing procedure. First, it is clear that it would be extremely advantageous to have an orbit -to-ground data link to permit the principal investigator to modify the control algorithms as the mission progresses. Currently, this capability is not available on the middeck, but various options are being investigated that may permit this. These options include partial use of the video signal channel or one of the communications channels.

The second point is that since it is desirable to maximize the number of tests run on-orbit, the testing procedure must be planned so that once a structural instability is reached using a particular control algorithm, testing can continue on-orbit while the instability is analyzed on the ground. This testing procedure is shown in the flow-chart in Fig. 4.4.5

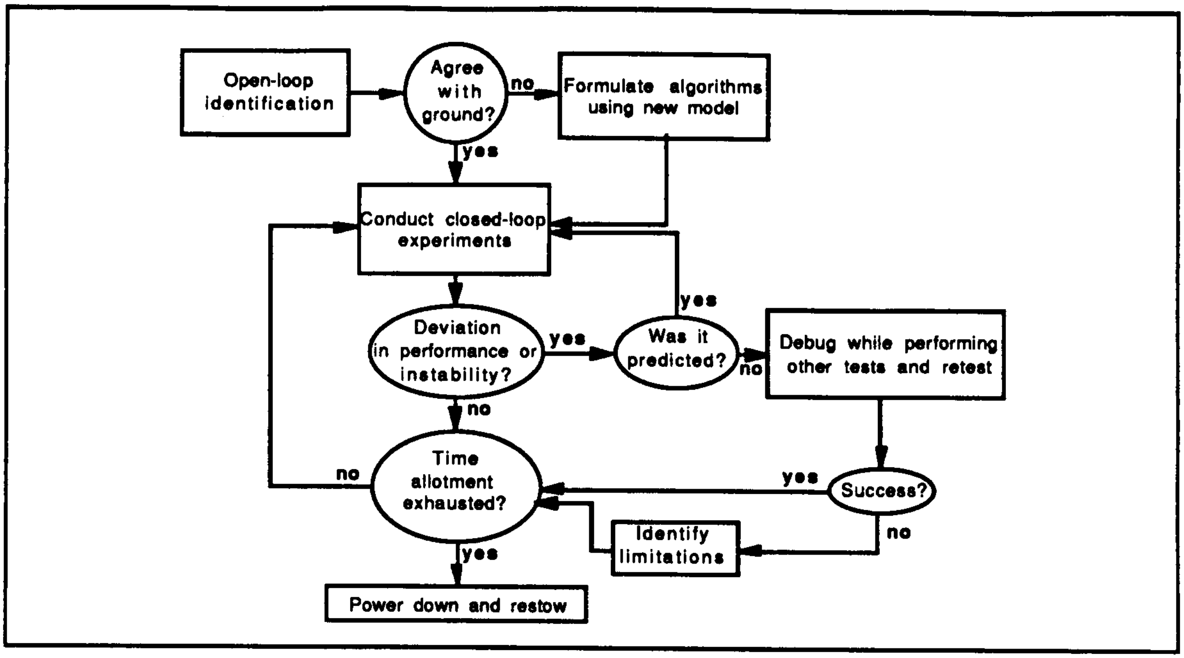


Figure 4.4.5 Testing procedure decision flowchart

The flowchart in Fig. 4.4.5 indicates the need to have available a data downlink capability from the middeck. As was mentioned in Chapter 3, this capability is currently unavailable, but a number of options, including the use of the video channel for short periods of time, are currently being investigated.

4.5 GROUND TEST PROGRAM

A flight test program is expensive, provides few data points, is performed in an environment which is rather inflexible with regards to test protocol and only results in brief test duration. Therefore, the test protocol should be well defined in order to obtain important data in a brief amount of time and this small amount of data must be correlated with other test data to ensure that the test article characteristics which are dependent on the Shuttle environment can be extracted and understood. In other words, a coordinated extensive ground test program is essential.

A ground test program for MACE is planned to begin in Phase B. As a Phase B effort, it will be instrumental in the development of the detailed design of the test article and supporting instrumentation. As shown in Figure 4.5.1, this ground test program is composed of nine phases: test article refinement; detailed design; prototype I fabrication; dynamic modelling; dynamic testing; control formulation; control testing; evaluation and prototype II fabrication. Each of these phases is discussed in the following sections.

4.5.1 Test Article Refinement

This preliminary phase (1 mos.) is used to address whether or not the test article selected in Phase A is still relevant to missions of interest to NASA or DoD. At this point, the test article can be altered or refined to be more relevant to existing programs.

4.5.2 Detailed Design

This phase (3 mos.) is used to formalize the test article design. Geometric, dynamic, static and disturbance characteristics are finalized. In addition, flight test procedures, control hardware and performance measures are defined. Mechanical and electrical components of the test article and Experimental Support Module are selected.

4.5.3 Prototype I Fabrication

This phase (4 mos.) involves the acquisition of hardware for the fabrication of the proof-of-concept ground prototypes of the test article, Experimental Support Module and test article suspension. The ground prototypes should be as representative of the flight test hardware as possible.

4.5.4 Dynamic Testing

This phase (5 mos.) involves the experimental validation of the various dynamic models to be used in the control formulation. This phase also investigates plausible procedures for predicting unconstrained on-orbit behavior from suspension constrained ground tests. This phase will couple closely with the control formulation phase. Dynamic testing is not restricted to this phase since, during the control testing phase, there will most likely arise a need to perform additional dynamic tests to enable improved performance or identify the causes of any instabilities which may arise.

4.5.5 Control Testing

This phase (6 mos.) involves the implementation of the formulated control algorithms. This phase overlaps the dynamic testing and control formulation phases since the debugging of the control system is an iterative process which involves implementation of the control, identification of limitations to performance, the conduct of additional required dynamic testing and the formulation of new control algorithms.

4.5.6 Dynamic Modelling

Once the definition of the test article is finalized and detailed design begins, dynamic modelling of the test article can commence (7 mos.). This model will be refined during the test article assembly and dynamic testing phases. Several types of dynamic models should be formulated as required for the analytical formulation of the various controllers chosen in the control formulation phase. These models can include modal, wave scattering, component, and impedance models. In addition, this phase includes the definition of the dynamic test procedures required during the dynamic testing phase.

4.5.7 Control Formulation

This phase (13 mos.) involves the formulation of the real time control algorithms which will be implemented on the test article. Work on the control algorithms can start during the detailed design phase once the dynamic properties and performance requirements of the test article become defined. Specifics of the algorithm can be adjusted during the dynamic testing phase as the dynamic parameters of the test article are determined more accurately.

4.5.8 Evaluation

This phase (3 mos.) provides a period for reevaluation of the flight test program based upon the findings in the ground test program. The ground test program should demonstrate sufficient capability to acquire meaningful data in a flight test program. In addition, the flight test program should be defined to provide data or capabilities which were not available in the ground tests. This provides the invaluable oppurtunity to make a midcourse correction to the flight test program using experimental experience obtained with prototype flight hardware.

4.5.9 Prototype II Fabrication

With the experience gained in the ground test program, a second prototype should be manufactured which is almost identical to the flight hardware (3 mos.) with constraints on power, volume and weight being adhered to. This allows the identification of any mission specific hardware problems prior to the point in the program when major design changes are discouraged (between the baseline PIP and the CIR).

A ground test program for Prototype II will follow the fabrication phase. This program will be similar to that performed for Prototype I. The primary focus of this program are to develop the on-orbit procedures that will be used during flight, to identify

any hardware and software incompatibilities that may exist between the experiment and the STS middeck, to measure the actual power used during the experiment runs, and to begin initial crew familiarity with the testing procedures and to collect the ground data that will be used for comparisons with the on-orbit results. This program continues for 11 months after the fabrication phase, and is not shown in Fig. 4.5.1

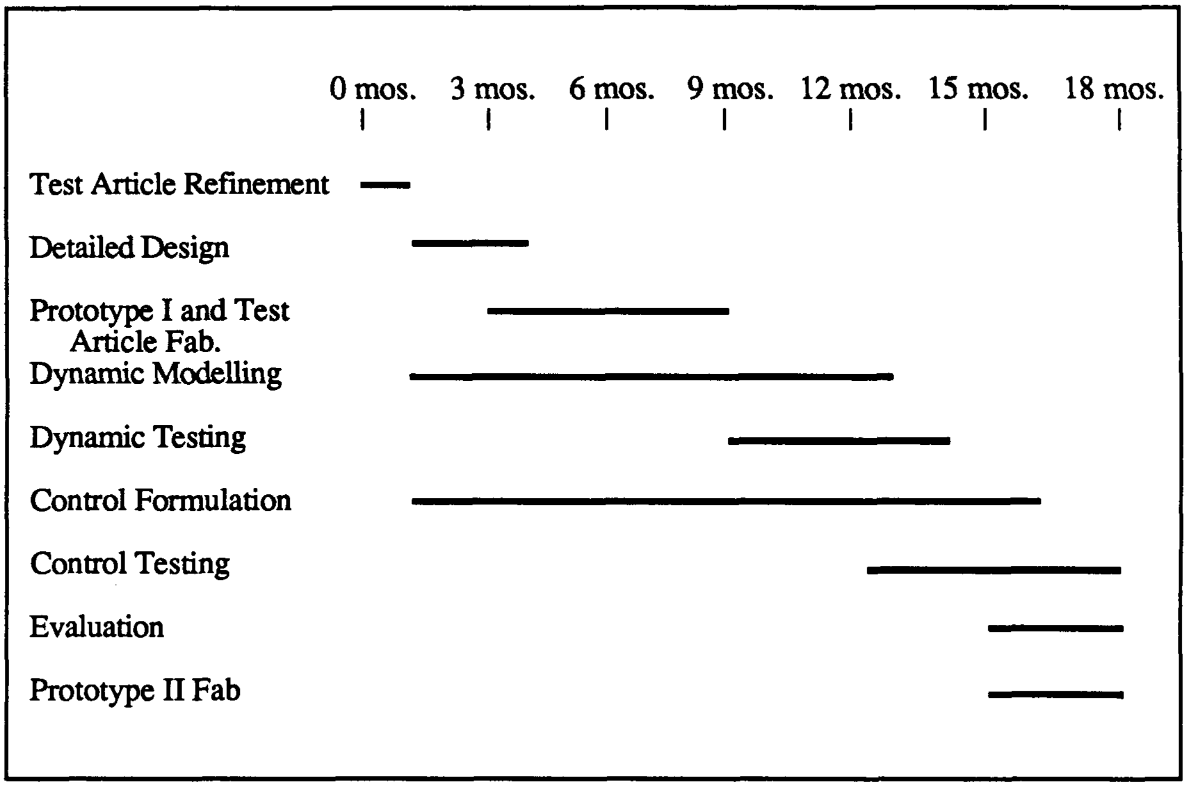


Figure 4.51 Phase B/C/D ground test program timeline. Prototype II testing continues for 11 months after Prototype II fab.

4.6 POST FLIGHT ANALYSIS

Data obtained from the first flight of the MACE experiment will be compared with both the predicted analytical behavior and the ground-test experimental data obtained during the Phase B and C/D periods of the program. If any significant deviations from the predicted behavior was observed during flight, the post-flight analysis phase will attempt to explain this behavior and possibly duplicate it during additional ground-tests. This is particularly important if the on-orbit open-loop identification experiments demonstrated any significant discrepancy between the ground-based and orbit open-loop structural behavior. If any instabilities were found during the on-orbit tests, these also will be duplicated, if possible, during post-flight ground tests.

In addition to the data obtained from the multibody test article, a post-flight analysis of the entire MACE system will be conducted to determine any faults or improvements that may be made to the facility in preparation for subsequent flights.

The detailed design of the reference multibody test article and the associated flight and ground test program is now complete. The MACE program, however, also includes fabrication of an Experimental Support Module. The design of this system will be presented in the following chapter. In addition, sensors and actuators that will be used by the test article will be surveyed, and candidate components will be selected.

Chapter Five: MACE Hardware Design

This chapter describes the process used to select a reference design of the MACE Experiment Support Module. It consists of four sections:

5.1 General Functional Description

5.2 Architecture Options

5.3 Implementation Options

5.4 Detailed Reference Design

The first section describes the functional elements of the experiment which are common to all architecture options considered for MACE. The advantages and disadvantages of these options are discussed in Section 5.2. The next section describes the primary and secondary recommendations for implementation of the architecture option chosen. A detailed discussion of two alternative implementations is given in Appendix C. Section 5.4 gives the details of the reference design, including an equipment list and schematic block diagram. A discussion of the specifications and requirements for computer-independent components (sensors, actuators, etc.) and the results of Payload Systems surveys of available components will be found in Appendix D.

5.1 General Functional Description

The general functions of MACE are shown in block diagram form in Figure 5.1.1. The experiment sequencer performs supervisory functions such as starting and stopping experiment runs, loading control algorithms into the DSP, selecting pre-determined amplifier gains, setting filter dynamics and excitation signal characteristics, and configuring the data acquisition device. The excitation source provides a disturbance signal to be input to the test article via torque motors and/or a disturbance actuator. Other actuators located on the test article are characterized as control actuators. These would include piezoelectric actuators embedded in the structure, linear proof mass actuators, rotary proof mass actuators, as well as gimbal torque motors used to position the payload elements.

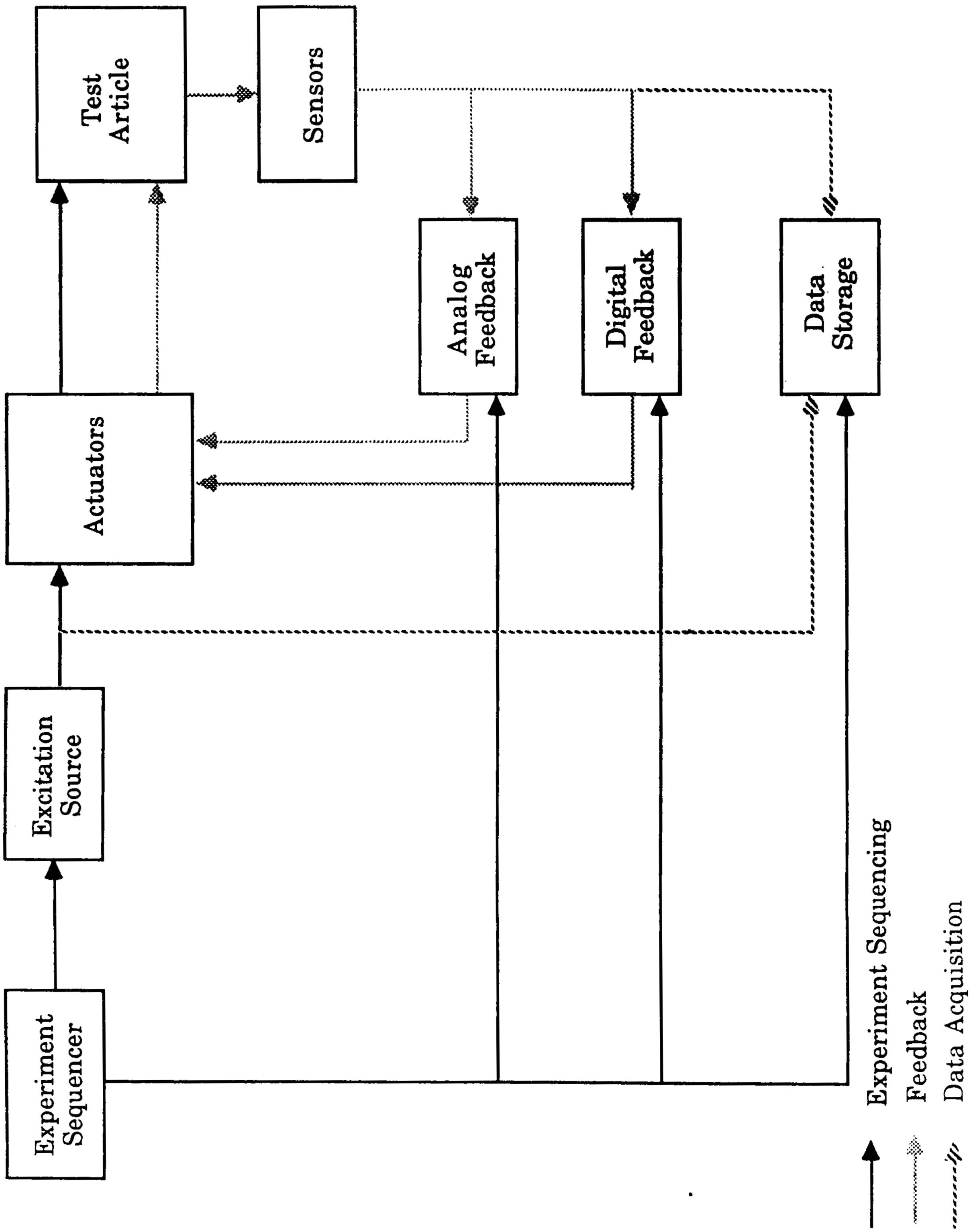


Figure 5.1.1 MACE Functional Block Diagram

Sensors on the test article will include angular velocity (rate) and position transducers at the gimbals, rate gyro triaxes in the payloads, load cells, accelerometers, and strain gauges.

The digital feedback loop contains a computer which performs the dynamics calculations required for test article control. An analog feedback loop will perform specialized conditioning of sensor signals for mixing with the output from the digital feedback module providing high bandwidth feedback.

The final functional block represents the data storage function. Sensor outputs and actuator input signals may be stored for later analysis, and switch settings and other 'housekeeping' information may be recorded for reference.

5.2 ARCHITECTURE OPTIONS

Four architecture options were considered for MACE:

- Discrete Instruments Approach
- Local Area Network Approach
- Master/Slave Approach
- Single Computer Approach

In the Discrete Instruments Approach, each of the functions described above is performed by a dedicated instrument. For example, a function generator would be used for signal generation, and a "stand-alone" computer would be used for the dynamics calculations. In the Local Area Network Approach, the discrete instruments are replaced with units which can communicate over a Local Area Network, such as the IEEE-488 (GPIB). The third option is the Master/Slave Approach, in which a dedicated microprocessor slave performs each of the functions. Each slave is under the supervision of a master, and communication between processors is accomplished over a common bus. This is the recommended architecture for MACE. The last option is the Single Computer Approach, which uses a single, powerful computer to perform all functions.

The advantages and disadvantages of each of these options are discussed below.

5.2.1 Discrete Instruments Approach

Figure 5.2.1 shows generally how the discrete instruments approach would be implemented. The "supervisor" is an astronaut, who sets a number of switches to configure the electronics for each experiment run and manually starts each run. The disturbance signal is

generated by a standard function generator, the output of which drives a power amplifier and the disturbance actuator itself. The analog feedback function requires specialized circuitry, and would therefore be a 'custom discrete instrument'. The dynamics calculations would be accomplished using a specialized computer capable of at least 3 MFLOP performance, with throughput adequate for the number and frequency of signal inputs. Analog to digital converters would be required for acquisition of sensor output signals, and digital to analog converters would be required to drive the actuators. A data storage system would record the sensor output signals, as well as switch settings and input signals, if possible. A separate set of analog to digital converters would be required if the data storage system has a digital recording format, as in an optical disc system.

The advantages of this approach include low cost and generally low power consumption, weight, and size. The human supervisor allows easy modification of test procedures, even on-orbit. The autonomy and relative simplicity would give good overall reliability.

The disadvantages include the difficulty of implementing complex test procedures, and the strong likelihood that each "off-the-shelf" instrument will require customization to meet interfacing, power, and mechanical requirements.

5.2.2 Local Area Network Approach

In this approach, each of the "discrete instruments" described above would be capable of communicating over a local area network such as the GPIB network used commonly in laboratories (see Figure 5.2.2). In this case, experiment sequencing is controlled by a network Host, which is responsible for experiment set-up, performance of experiment protocols, and supervision of data acquisition and storage functions. Each of the separate experiment functions would be performed by a network Node.

The functional modules in this approach can be as autonomous as desired, depending on the capability of the available instruments. Complicated experiment sequencing tasks can be programmed with relative ease using commercially available software. The architecture is also flexible in that Nodes may be added, removed, or modified with minimal impact on the rest of the system.

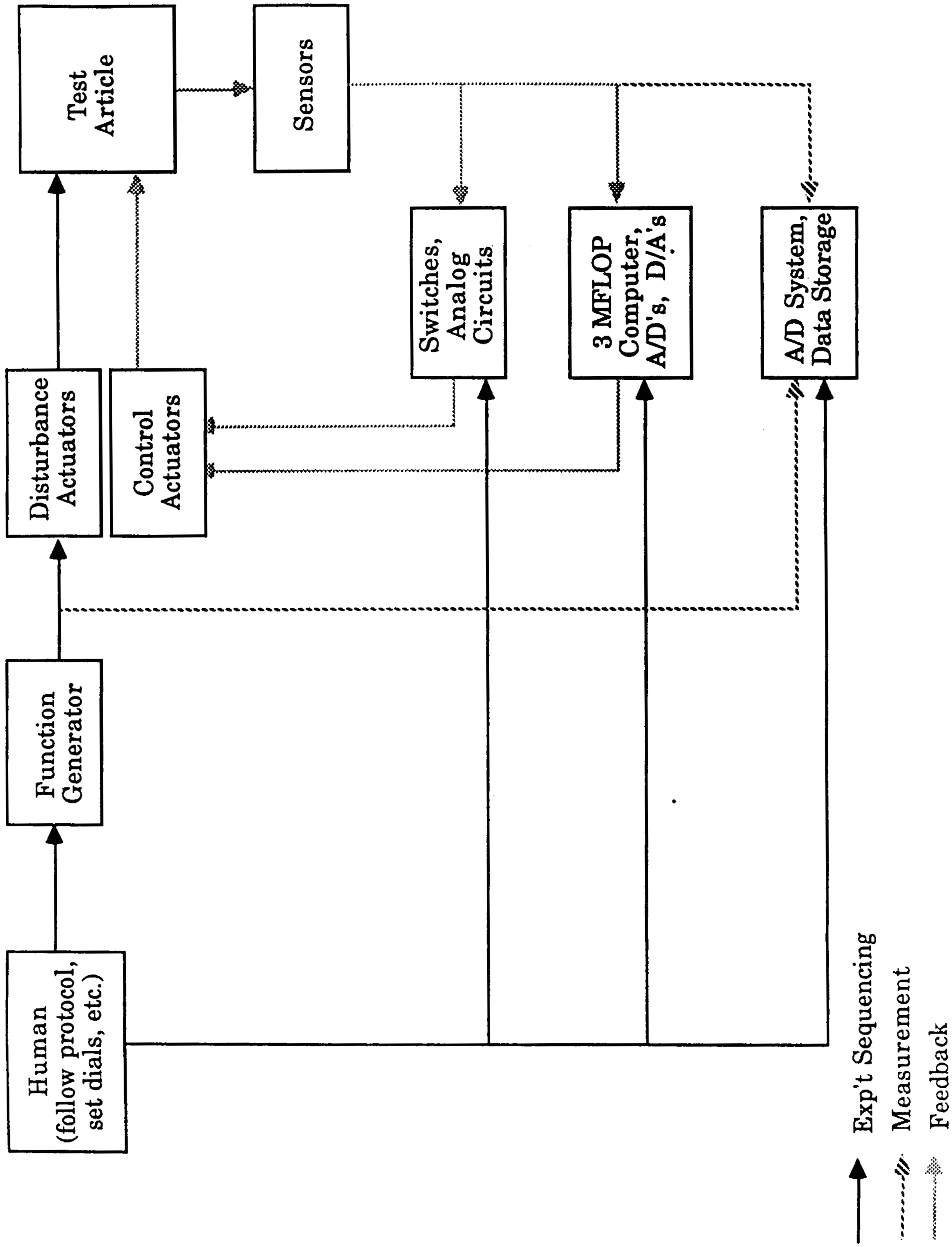


Figure 5.2.1 Discrete Instrument Approach

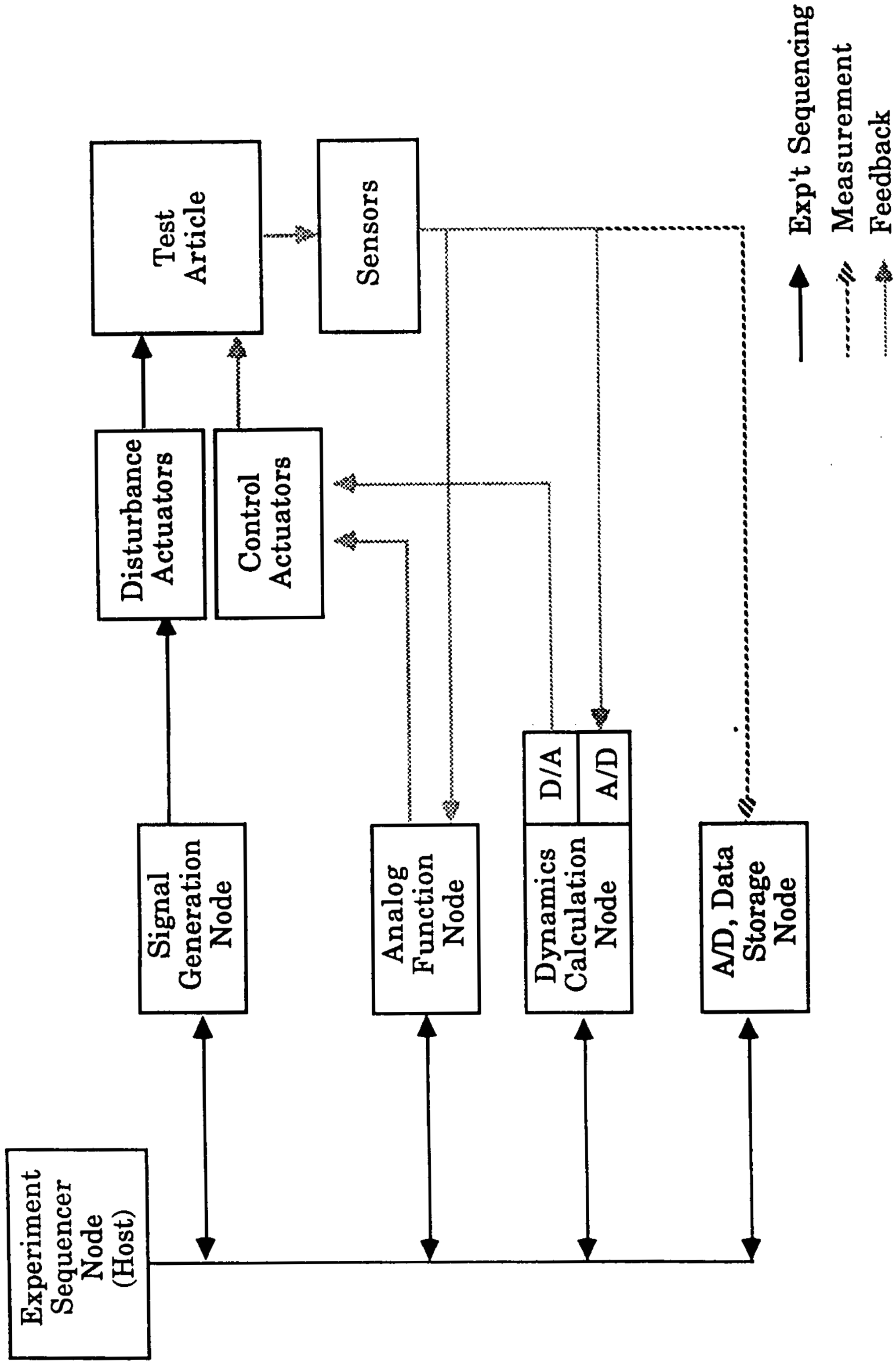


Figure 5.2.2 Local Area Network Approach

The LAN approach has the disadvantage of requiring extra software and hardware to provide the communications interface. This is especially significant when standard instruments are not available with the chosen network capability. For example, if a GPIB network is used, it is expected that standard instruments will easily meet the signal generation requirements. However, a separate GPIB interface must be added to the Dynamics Calculation Node and to the Data Storage Node to allow communication with the Host. In addition, a custom GPIB interface must be designed to implement the Analog Function Node. Since network communications generally require microprocessors to perform the interface function, this significantly increases the complexity of this module.

5.2.3 Master/Slave Approach

Figure 5.2.3 shows the Master/Slave architecture. Generally, a separate microprocessor is dedicated to each function, and these processors communicate over a bus, such as the STD or IBM PC-AT. The Master provides supervision (e.g. start, stop, reset) of all functions, and is responsible for all interprocessor communications. It should be noted that simple digital input/output functions may be implemented without using a microprocessor, through the use of direct logic circuit interfacing to the bus. Dynamics calculations would be performed by a Coprocessor Slave, with digital-to-analog (D/A) and analog-to-digital (A/D) converters located on the slave. This approach would keep the large volume of data generated by the coprocessor from being transferred over the bus. A separate A/D will be used to acquire signals to be packaged by the Data Storage Slave and stored in the Data Storage Peripheral. Bus throughput will be dedicated primarily to this data stream, and otherwise will be used for parameter setting and experiment start/stop commands.

The advantages of the Master/Slave Approach include the commercial availability of high speed slave processors, and the large variety of available hardware functions. Each slave is "smart"; failure in the master does not imply failure of the slave. Busses are available which are good choices to meet middeck locker size and power constraints. The architecture is flexible, and complex test procedures may be implemented with relative ease. Note that modifications to a particular slave do not necessarily require modifications to the master. This allows design improvements to be implemented easily.

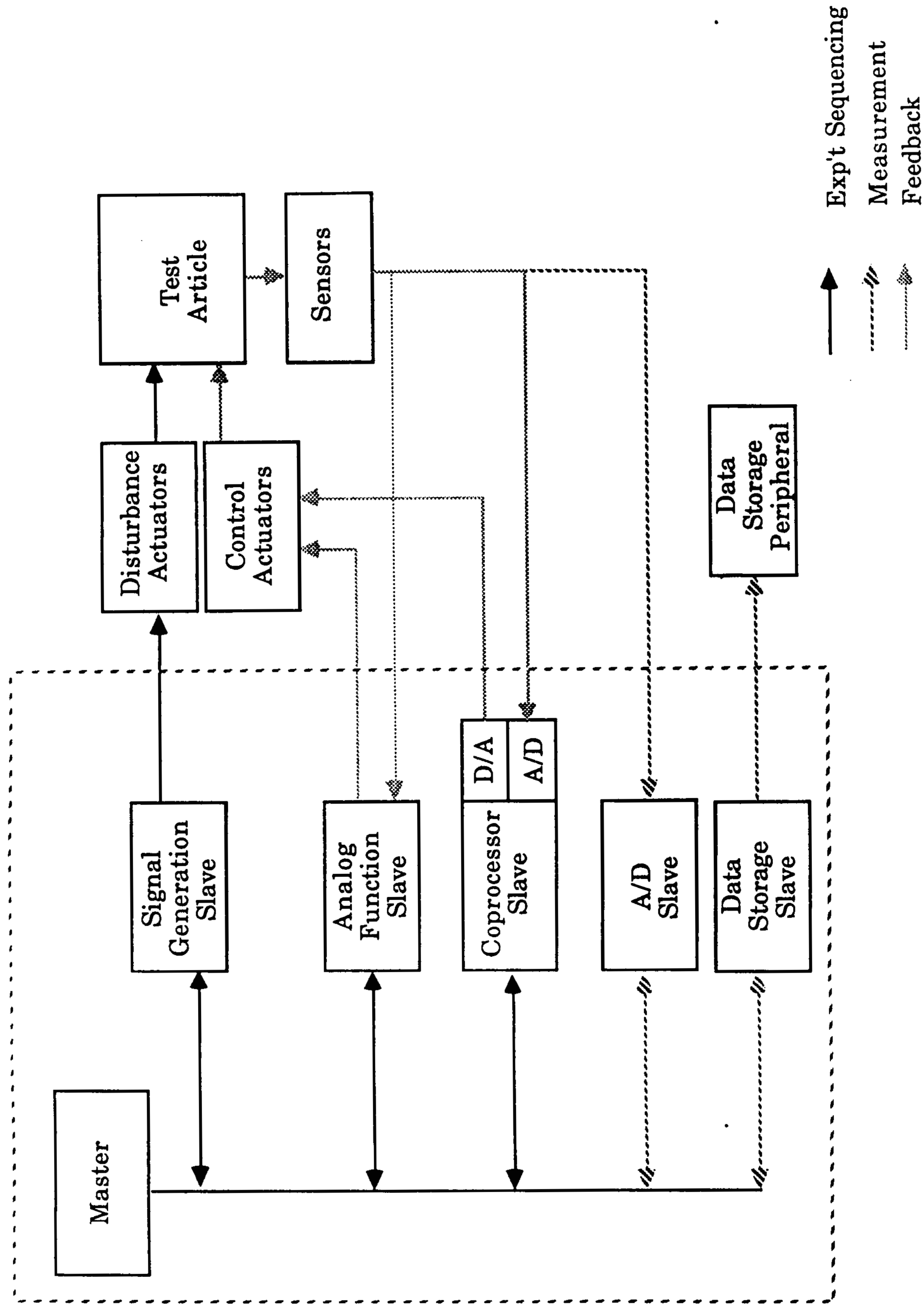


Figure 5.2.3 Master/Slave Approach

5.2.4 Single Computer Approach

Figure 5.2.4 gives a block diagram of a MACE architecture which uses a single, high speed computer to perform all experiment functions. Specialized hardware modules for digital to analog conversion, analog to digital conversion, signal generation, and data storage would be fully controlled by a single processor with dedicated software for each function.

The advantages of this approach include the high degree of flexibility, while hardware remains relatively simple. A 'virtual' architecture such as this would permit highly complex test procedures, and changes to the procedures would require only software modifications.

The disadvantages center around the single, complex program used to perform the experiment functions. The critical digital feedback loop includes the main processor, thus a single software bug would represent a single point failure of the experiment. Development, debugging, and modification of the main program will be costly, as these require extensive effort on specialized computers.

5.3 IMPLEMENTATION OPTIONS

The evaluation of architecture options performed above strongly suggests that the Master/Slave Approach is the best approach for MACE. The Discrete Instrument Approach would likely require extensive customization to meet the various interfacing and power reuqiremets. The LAN Approach carries along a large power and complexity overhead due to the need for separate microprocessors to perform the interface function. Finally, the Single Computer Approach would likely require extensive software development on specialized computers, and would present a single point failure if any software bugs where to be present.

The Master/Slave architecture can support a wide variety of experiments, even those not currently envisioned. It can support multiple experiments, each with radically different test articles. This flexibility results from utilization of separate microprocessors for each of the following major functions:

- System supervision
- Signal generation
- Digital control
- Data acquisition
- Data storage

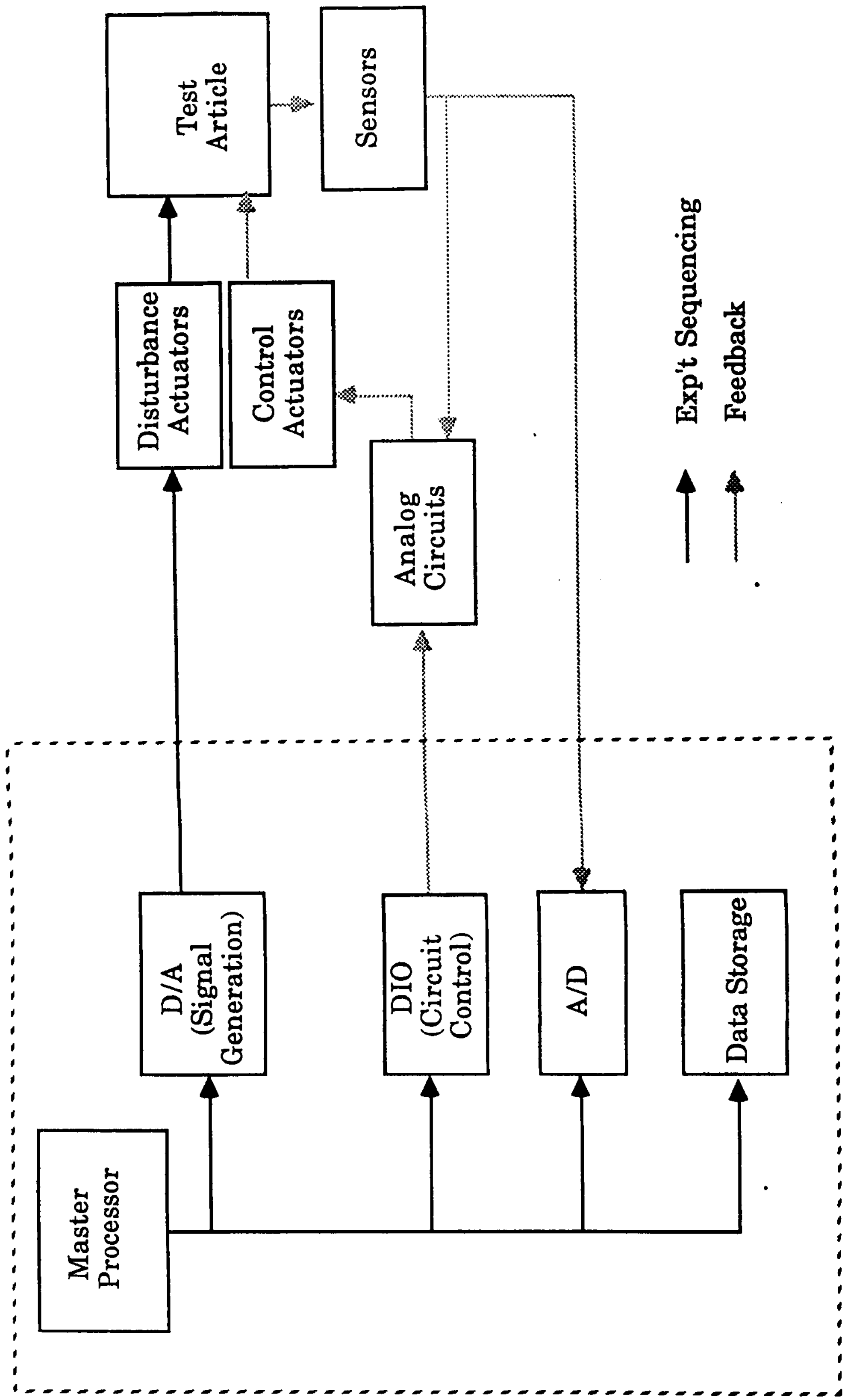


Figure 5.2.4 Single Computer Approach

Three options for implementation of the Master/Slave architecture were considered. These are the STD bus, the IBM PC-AT bus, and the SCI MAST 1750A computer. These options are compared in Table 5.3.1. Note that STD and AT busses are practically identical in power, hardware and software development cost, capabilities, and reliability. The MAST computer, however, has a high software and hardware development cost associated with it, since it is primarily a "one-of-a kind" machine developed for the COFS program. A flight qualified version of this computer is available through NASA Langley free of charge. However, the additional copies necessary for hardware backup and crew training would have to be purchased from the manufacturer. In addition, the weight of the computer is approximately double that of the STD or AT bus. The main advantage of the MAST is that architectures based on either of these computers would benefit from the low risk in using hardware which has been developed specifically for flight. In general, therefore, this system requires substantial software development efforts on highly specialized computers. Although the personnel and equipment can be made available if the MAST is used, changes to the software will be difficult to implement as the experiment matures. This will greatly restrict the ability of investigators to improve experiment performance late in the development process. For these reasons, the MAST computer was not selected.

The primary recommendation is the STD bus architecture is depicted in Figure 5.3.1. Note the high degree of similarity between this architecture and that depicted in Figure 5.1.1 (functional block diagram) above. The only function that does not have a processor dedicated to its requirements is the analog feedback; this is reasonable compromise, as the only processing requirements expected are setup actions prior to experiment execution. A detailed discussion of the STD bus architecture as applied to MACE is given in Appendix C. Table 5.3.2 gives a listing of representative specifications and prices for the major components of an STD based system.

The major features and benefits of the STD bus approach are summarized below:

- Easy to program individual functions
- Each function is capable of high performance
- Each function implementation may easily be replaced by a new design, with minimal impact on the overall system
- Each function may be removed (except the supervisor) if not needed without impact on the overall system

Table 5.3.1 MACE Architecture Options Comparison

MACE Architecture Summary

Option	HW Cost	HW Develop Cost	SW Develop Cost	Power	Size	Weight	Technical Risk	Space Qualif.	MFLOPs	Reliability
STD Bus	$14,939	Moderate	Low	64 W	1025 cu. in.	12.5 lbs	Low to Moderate	Moderate	33.3	Moderate
AT Bus	$16,538	Moderate	Low	71 W	1173 cu. in.	14 lbs	Low to Moderate	Moderate	33.3	Moderate
MAST	$210,149	High	High	72 W	1222 cu. in.	30 lbs	Moderate to High	Easy	16.67	High

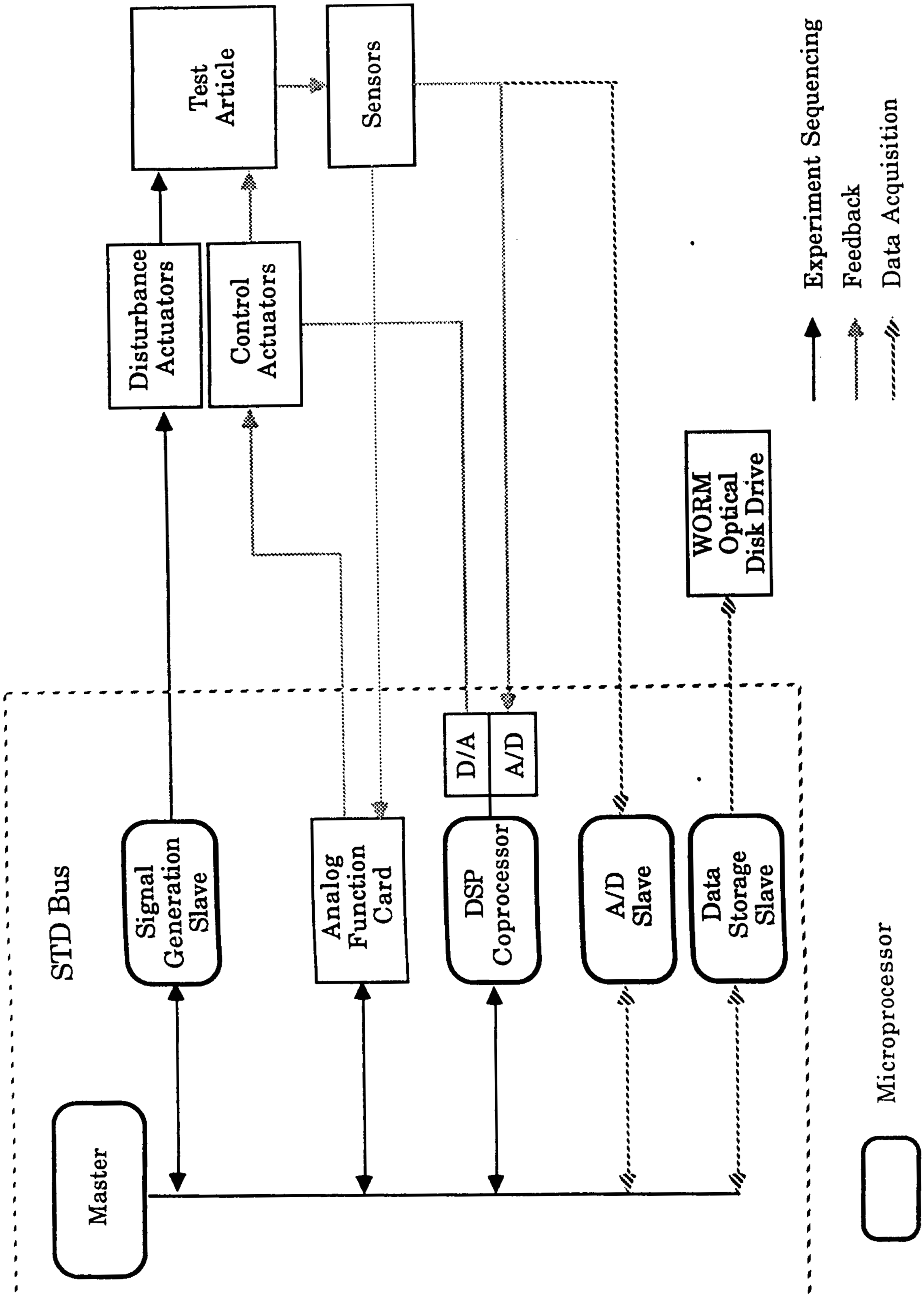


Figure 5.3.1 STD Architecture

Table 5.3.2 STD System Component Summary

Primary Option STD bus

Component	Cost	Power	Size	Weight	Technical Risk	Performance	Comments
Exp't Sequencer							
ZT8815 Processor	$410	3.25W typ	4.5" x 6.5"	~ 7 oz.	Low	8 MHz 80188	32k ROM
zSBX30 DIO iSBX card	$110	1.2W typ	3" x 3.5"	~ 2 oz.	Low	48 bit I/O	2.2 MHz max. data rate
Signal Generation							
VDS-8	$1,250	6 W	4.5" x 6.5"	<8 oz.	Low	1 mHz steps	req's control program
Analog Feedback							
Custom Circuits	Custom	1 W	4.5" x 6.5"	<8 oz.	Moderate	Program control of ckt parameters	
Data Acquisition Slave							
ZT8832 Processor	$650	5W typ	4.5" x 6.5"	~ 7 oz.	Low	8 MHz V40	64k ROM
CDX-AD816 iSBX	$545	1 W	2.9" x 2.7"	1.6 oz.	Low	12 bit, 10 kHz/ch.	8 differential or 16 single ended inputs
Data Storage							
ZT8832 Processor	$650	5W typ	4.5" x 6.5"	~ 7 oz.	Low	8 MHz V40	64k ROM
ZBX 288 SCSI iSBX	$175	2W typ	2.9" x 2.7"	1.6 oz.	Low	DMA @ 1.5 Mbytes available	8 bit word size
SEL-2 WORM drive	$7,149	27W	7"x 8"x 11.4"	9.8 lb.	Low	200 Mbytes/side	195 msec access time space qualified version avail.
Dynamics Processor							
TI320C30 DSP Board	Custom	5W typ est	4.5" x 6.5"	~ 8 oz.	Moderate	33 MFLOPs Peak	TI TMS320C30 DSP Chip
A/D and D/A Board	Custom	7.5W typ	4.5" x 6.5"	~ 8 oz.	Moderate		

- Each function is physically separate from all others, communicating only through a well-defined interface, thus promoting independent development with straightforward integration
- The STD bus is a widely utilized, industry standard
- Many cards commercially available
- The STD bus utilizes a small (4.5" x 6.5") form factor card
- Low cost, low power, and minimal developmental risk

The secondary recommendation is based on the IBM Personal Computer AT bus architecture, and is shown in Figure 5.3.2. Again, notice the similarity between this option and that of Figures 5.1.1 (functional block diagram) and 5.3.1 above. The major difference between this option and the STD version, besides the different bus, is that only two processors are used in this architecture. Providing a separate processor for each function would require a significant development effort, as currently available systems will not fully support this approach. Each experiment function can be implemented using specialized cards which reside on the bus, however the Master processor will be required to provide software control of these functions. In implementation, the PC-AT option therefore becomes similar to the Single Computer approach, except that the dynamics calculations are performed on a separate co-processor.

A detailed discription of the PC-AT bus architecture as applied to MACE is given in Appendix C. Table 5.3.3 gives a listing of representative specifications and prices for the major components of a PC/AT based system.

The major features and benefits of this approach are summarized below:

- Wide variety of sophisticated, high quality hardware and development tools, driven by the extremely large personal computer market, are available for the PC-AT bus
- The PC-AT bus is a widely utilized, industry standard
- Low cost, low power, and minimal developmental risk

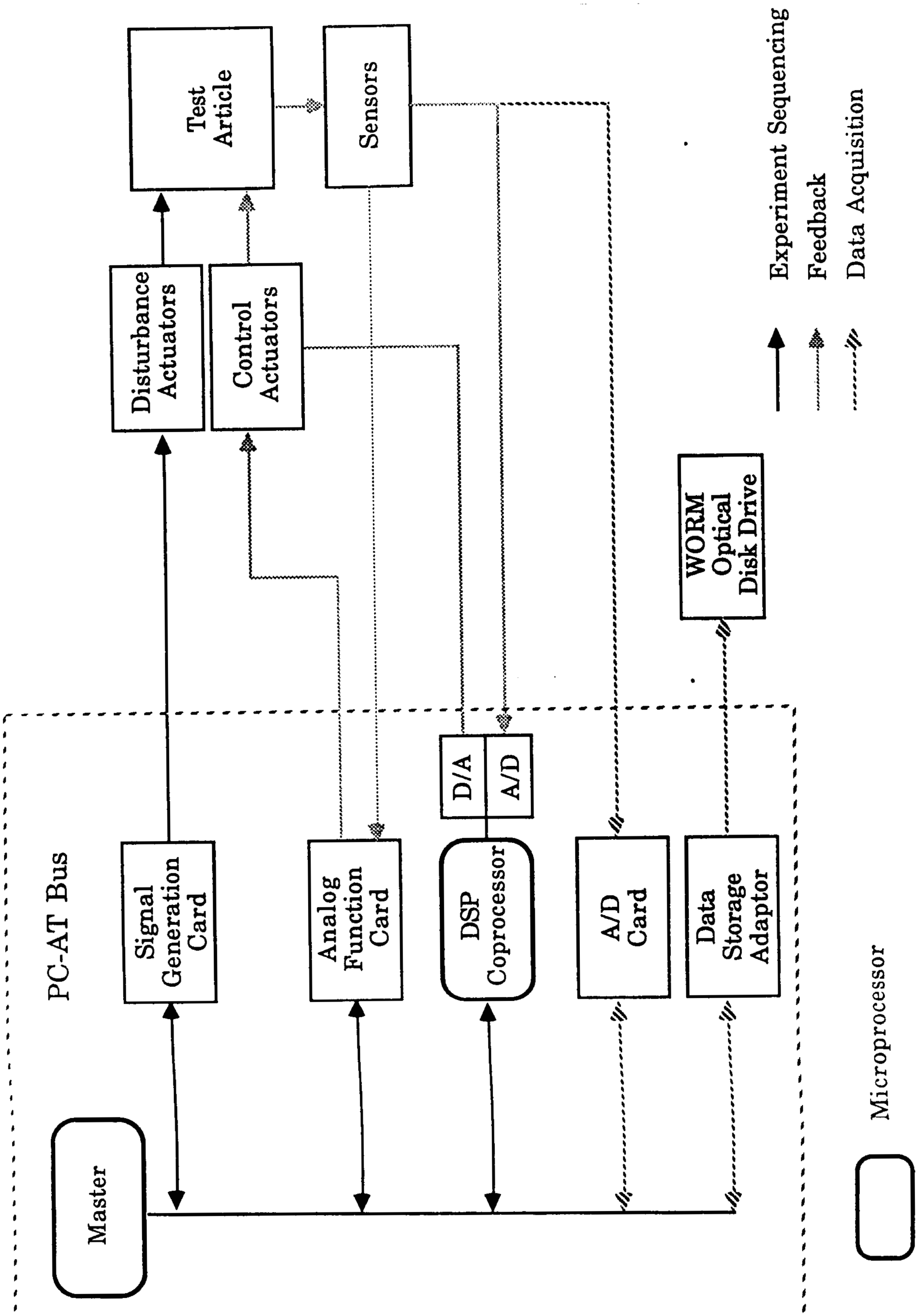


Figure 5.3.2 PC/AT Architecture

Table 5.3.3 AT System Component Summary

Secondary Option AT Bus

Component	Cost	Power	Size	Weight	Technical Risk	Performance	Comments
Exp't Sequencer							
QPC 5132 Processor	$1,195	12 W typ	4.7" x 13.3"	~ 1 lb.	Low	12 MHz 80286	up to 4 Mbytes RAM avail.; SCSI interface on board
DT2817 DIO card	$199	3W max	4.7" x 5"	< 8 oz.	Low	32 I/O lines	
Signal Generation							
VDS-8-PC	$2,000	7 W est	4.7" x 13.3"	< 8 oz.	Moderate	Same as VDS-8	On board control program; available 6/89
Analog Feedback							
Custom Circuits	Custom	1 W est	4.5" x 6.5"	<8 oz.	High	Program control of ckt parameters	
A/D Card							
DT2821 A/D card	$1,995	9W typ	4.7" x 13.3"	20 oz.	Low	12 bit, 150 kHz throughput	8 differential inputs; 250 kHz throughput avail.
Data Storage							
SEL-2 WORM drive	$7,149	27W	7"x 8"x 11.4"	9.8 lb.	Low	200 Mbytes/side	195 msec access time
Dynamics Processor							
TI320C30 DSP Board	Custom	5W typ est	4.7" x 13.3"	~ 8 oz.	Moderate	33 MFLOPs Peak	TI TMS320C30 DSP Chip
A/D and D/A Board	Custom	7.5W typ est	4.7" x 13.3"	~ 8 oz.	Moderate		

The PC/AT was not chosen as the primary option was due primarily to the large experience that exists both at MIT SERC and at Payload Systems in using STD computers in the laboratory. Many of the components required for the STD bus have already been used in various active control experiments at MIT. For this reason, it is felt that the STD bus provides the greatest amount of capability for the least amount of cost and development risk.

5.4 Detailed Reference Design

Comprehensive surveys in each of the critical areas of MACE hardware were performed. The primary purpose of these surveys was to insure that the measurement and control objectives of the experiment can be met with existing technology. The areas of interest were

- Angular rate transducers
- Angular and linear accelerometers
- Strain gauges
- Torque motors
- Angular position transducers
- Force transducers
- Transducer powering and signal conditioning
- Excitation signal generation
- Power amplifiers
- Data storage
- Power supplies (DC to DC converters)
- Custom circuitry

The sections which follow are summaries of the results of these surveys. They describe the specifications and requirements which were followed in the collection of this information. In most cases, the particular items listed are meant to demonstrate the availability, functionality, and cost of the components, and not to suggest a particular design implementation. When the surveys were complete, components were chosen from these lists and a reference design developed. A schematic block diagram was developed which shows how these components form a basic design which meets the experiment requirements.

5.4.1 Component Surveys

5.4.1.1 Angular Rate Transducers

Angular motion of the articulated payload elements will be measured as they are slewed. Measurement of the angular velocity can be made from rate gyroscopes or solid state rate transducers. The specifications used in the survey of these transducers are listed below.

- Angular Range: $\pm 90°$
- Resolution: 0.57°/sec
- Slew rate: $\pm 570°$/sec
- Frequency Response: 20 Hz minimum

The results of Payload Systems' survey of available rate transducers are given in Appendix D, Table D.2.1

5.4.1.2 Angular and Linear Accelerometers

In general two types of accelerometers, angular and linear, might be used in MACE. Angular accelerometers may be used on the articulated payload elements to augment the rate transducers listed in Appendix D. These have limited bandwidth, generally on the order of 20 Hz. Angular accelerometers may be used in conjunction with the rate transducers in order to increase the effective measurement bandwidth. Angular velocity may be derived electronically from the output of the accelerometers, which is proportional to angular acceleration. Linear single-axis and triaxial accelerometers might be used elsewhere on the test article to record disturbance inputs or other structural vibrations.

The specifications for accelerometers are listed below.

- Range: 10^{-4} to 10^{-1} g
- Resolution: 10^{-4} g
- Sensitivity: 1 to 100 mV/g minimum (assumes one volt bipolar A/D converter with 12 bit resolution, amplifier gain 50 to 5000).
- Frequency response: 0.1 to 500 Hz (useable)
- Weight: 30 grams maximum
- Size: Accelerometers must not constrain test article motion or assembly.

A summary of the results of Payload Systems' survey of available angular and single-axis linear accelerometers is given in Appendix D, Table D.2.2. It can be seen from this data that, in general, weight and size increase with bandwidth and resolution. The piezoresistive (PR), variable capacitance, and servo types will measure static accelerations but have limited high frequency response. It should be noted that most units, other than the piezoelectrics, behave like second order systems in terms of phase response, however the frequency response given often includes the effects of error sources such as thermal drift, and so is conservative. Note also that lighter PE accelerometers are available, but these require charge amplifiers located close to the sensor head in order to prevent susceptibility to noise pickup in the cabling.

The results of a survey of triaxial accelerometers are given in Appendix D, Table D.2.2. The servo units are quite capable of achieving the required resolution, however they are relatively heavy, more expensive, have smaller bandwidth, and consume more power than other units. Note also that three single axis accelerometers may be mounted together to form a three axis system. This has the advantage of allowing the signal conditioning to be the same as for the single-axis accelerometers.

5.4.1.3 Strain Gauges

Strain gauges located at various positions on the test article will allow measurement of structural element bending, axial, shear, and tortional strain. The tranducers used will be standard resistive foil types, available commercially in a wide variety of sizes, shapes, and sensitivities.

5.4.1.4 Torque Motors

Torque motors will be used to position the articulated payload elements on the test article. The specifications used in the survey are listed below.

- Range: $\pm 90°$
- Peak Torque: 1.25 lb-ft minimum
- Frequency Response: 0 to 1 Hz
- Size: Must be incorporated into test article structure

A sampling of available torque motors suitable for MACE is listed in Appendix D, Table D.2.3

5.4.1.5 Angular Position Transducers

Standard potentiometers will be used to measure angular position of the articulated payload elements. These will be driven by a high level (±10 V typical) DC voltage, and will output a high level (± 5 V typical) signal proportional to the angular position of the element. Many rate gyros have these potentiometers within the same housing, eliminating the need for separate components and wiring.

5.4.1.6 Force Transducers

Measurement of forces applied to the test article from a shaker or other displacement transducer may be required. Standard piezoelectric force tranducers with standard stud or bolt mounting would be used. The specifications used to survey the currently available force transducers are listed below.

- Range: ± 10 lb.
- Resolution: 0.02 lb.
- Sensitivity: 500 mV/lb, desired.
- Frequency Response: 0.1 to 1000 Hz, min.
- Size Must not constrain test article motion or assembly.

The results of the survey are given in Appendix D, Table D.2.4 The results show that the specifications can be met with a variety of mounting types, provided that sensitivities below 500 mV/g are acceptable.

5.4.1.7 Transducer Powering and Signal Conditioning

The large number of sensors (16 to 32) to be mounted to the test article requires that the size, weight, and power consumption of signal conditioning amplifiers and transducer power supplies be kept to a minimum. Furthermore, conditioning amps will not be located on the test article. They must be located in the middeck locker with other electronics.

Signal to noise ratio at the conditioning amp inputs will depend on cable length, shielding type and efficiency, and sensor signal output level. Cable length from sensors to amps will be maximum for any sensor at the farthest point from the umbilical attach point. A cable length of several meters is therefore assumed. This has some impact on the choice of sensor type, as low level output signals (e.g. from unamplified piezoelectric accelerometers or

force tranducers) will be more susceptible to electromagnetic noise pickup, thus reducing resolution. It is therefore desirable to select sensors with high level outputs wherever possible.

It is assumed that some buffering of sensor signals will be required, in order to match sensor output levels to those required by the analog to digital converter inputs. Low pass (anti-alias) filtering will also be required. This type of signal conditioning is considered standard, and would require a small amount of space and power (on the order of one or two 4.5 x 6.5" circuit cards and 1 or 2 watts of power).

The results of Payload Systems' survey of transducer powering and amplification are given in Appendix D. Table D.2.5. The rate gyroscopes will require significant power, as can be seen from the rate transducer survey. For example, the Dual Axis Rate Sensor requires about 10 watts for startup and 2 watts during operation. A 400 Hz, 26 V, 2 phase signal must be available for powering the detector and spin motor. Solid state units, including the magnetohydrodynamic sensor, use significantly less power.

Strain gauges may be excited using a hybrid circuit such as the Analog Devices 1B31. This 28 pin DIP contains a precision instrumentation amplifier with adjustable gain, a two-pole low pass filter with adjustable cutoff frequency, and adjustable transducer excitation voltage. The output may be fed directly to an analog to digital converter input.

For accelerometers, many of the units listed in the Accelerometer Survey do not require anything other than well regulated DC power derivable from the (unregulated) +28 VDC available in the middeck, and will provide a high level signal output. Amplification, if required, can be provided with custom circuitry or with various types of modular units, many of which are designed for airborne applications. For piezoelectric types, a charge amplifier is required, and should be placed as close to the sensor head as possible to minimize noise.

For force transducers, the type of power conditioning required depends on the transducer type. Because the number of force transducers is expected to be small, the modular units available generally can meet the power, size, and weight specifications.

The torque motors will require a large current signal. The voltage command may originate in a digital to analog converter, followed by a power amplifier. Power amplifiers are discussed in section 5.4.1.9 below. Similar units may be used to drive an electrodynamic shaker, if one is employed as a disturbance source.

5.4.1.8 Excitation Signal Generation

For the generation of sine wave and sine-sweep signals over the 0.1 to 500 Hz frequency range, a digital frequency synthesizer may be used. The particular models listed in

Appendix D, Table D.2.6 have a DC to 80 kHz bandwidth, with sweep steps as small as 0.001 Hz. Frequency is controlled with a parallel, BCD TTL logic level input. This is easily generated with a Digital Input/Output module in any of the computer architectures discussed for MACE.

The VDS-8-PC is capable of generating a variety of waveforms, including square, pulse, and sine x/x. This card also has programmable attenuation of the 10 V peak-to-peak output in 0.125V steps. In an STD architecture, the VDS-8-PC may be controlled over a GPIB (IEEE-488) interface. Alternatively, discussions with the manufacturer indicate that it is possible to program the on-board ROM used in the VDS-8 with waveshapes other than sine waves.

The third item in the survey is typical of the available programmable function generators. It is capable of performing programmed sine sweeps, and is GPIB controllable. However, the unit is designed for 110 VAC operation in a laboratory, and so would require considerable modification for use in the middeck locker.

Generation of a large variety of excitation signals may be accomplished using a dedicated microprocessor, such as those employed in the STD architecture, driving a digital to analog converter. Low pass filtering of the output may be required, depending on the frequency range and purity of the desired output signals. This would be accomplished using filters located on the DAC circuit card.

5.4.1.9 Power Amplifiers

Amplification of the excitation signal to the levels required by the torque motors will be required. This is most easily done using single package, high power op amps of the type listed in Appendix D, Table D.2.7. The devices listed are typical of a large variety of power op amps available for various output voltage and current ranges, bandwidths, and packaging styles.

Heat sinks will be the major component of weight and size, and must be chosen to match the expected power dissipation and desired case temperatures. The lack of convective cooling must also be considered in the selection of heat sink approaches. Generally, rejecting heat to the cabin air is the only means of cooling available to standard middeck payloads. This would be done with small piezoelectric fans.

The possibility of using the experiment container (the metal structure which holds the electronics to the avionics bay bulkhead) as a heat sink should be pursued with Payload Integration personnel as the Payload Integration Plan is developed. This would save the considerable size and weight of providing heat sinks.

C-2

5.4.1.10 Data Storage

A minimum of 8 channels of data will be required to bring useful data to the ground, with 16 channels considered very desirable. The need for a large number of data channels greatly reduces the number of units which will meet the requirements within the size, weight, and power constraints of the middeck locker. There are four possible approaches: analog (FM) tape, Pulse Code Modulated Digital Audio Tape (PCM DAT), video recorders, and optical disc drives.

In Appendix D, Table D.2.8, the results of Payload Systems' survey of data storage systems in these four areas is given. Clearly, the FM tape approach requires the least power, however retrieval of data from these tapes is a difficult and time consuming process. In addition, the tapes have limited shelf life and are susceptible to accidental erasure, breakage, and stretching. The PCM DAT systems offer improved frequency response and store the data in digital form, but are large and heavy, as they are not designed for space flight. Video recorders are available which are ruggedized for flight, offer wide bandwidth, and long record times. However, these units require interface circuitry to allow analog signals to be recorded in the video format. This is done using an analog to PCM converter, which feeds a PCM to video converter, and this process is seen as overly complicated and requires about 50 watts of power with presently available units.

The optical disc approach allows data to be stored from a digital data acquisition system which will be resident in the computer card cage. The number of channels recorded is limited only by the D/A converter and the bus throughput. Typically the data is stored in packets, which may include information about the signal source, time tags, error messages, etc. A single optical disc will record 200 Mbytes of data per side. Assuming 16 channels of data, a sampling rate of 5000 samples per second (per channel), and 16 bit samples, 21 minutes of data may be recorded on one side of a disc. The Mountain Optech SEL-2 listed in the Appendix is a ruggedized drive. A space qualified version is currently being developed by the manufacturer, and is expected to have reduced weight and lower power consumption.

5.4.1.11 Power Supplies

The devices listed in Appendix D, Table D.2.9 are intended to show that power supplies are readily available in forms which are suitable for flight. The MACE hardware generally will require differential power sources such as ± 15 VDC, ± 12 VDC, and single ended power such as +5 VDC and +24 VDC. These may all be derived from the Shuttle supplied +28 VDC with the use of DC to DC converters. Some units are available with multiple outputs, but a small number of these units will be required in any case in order to

provide the full 115 watts expected to be required by MACE. It should be noted that Shuttle power is unregulated, i.e. specifications are given as 28 VDC ± 4 V for continuous loads under 115 watts. Voltage drops with increasing power consumption, as depicted in NSTS 21000-IDD-MDK, page 7-2.

5.4.1.12 Custom Circuitry

Custom circuitry will be required to provide three distinct functions. These are digital control of amplifier gains, buffering and low pass filtering of sensor output signals, and analog feedback (i.e. filtering of signals output from the dynamics processor and signal generator).

It is assumed that these circuits will be constructed on circuit cards of the same size and type as those used in the main computer card cage. Power will be supplied from the computer bus as well. The estimated size, weight, and power consumption of these circuits are given in the Equipment List, Table 5.4.1 in Section 5.4.3.

5.4.2 Schematic Block Diagram

Figure 5.4.1 gives a schematic block diagram of a reference prototype design for MACE. This design is based around the STD architecture option, and uses five separate microprocessors to accomplish experiment sequencing (Master), signal generation (Excitation Slave), dynamics calculation (DSP Coprocessor), data acquisition (Data Acquisition Slave), and data storage (Data Storage Slave). Each processor has an iSBX bus port which can be used for function cards dedicated to specific tasks, such as digital to analog conversion or other input/output functions. Parallel ports are also available on each microprocessor card for direct digital communications.

Provisions are made for direct uplink of slave programs and parameters through an RS-232 link to the Master. Furthermore, astronaut interaction is possible through the use of switches and LED's driven by a digital input/output function card connected directly to the iSBX bus on the Master.

The Excitation Slave is a dedicated microprocessor providing software generated waveforms, which are converted into analog signals by a digital to analog converter (D/A) card connected via the iSBX bus. Smoothing filters will be located on the iSBX card to eliminate high frequency components associated with the D/A conversion.

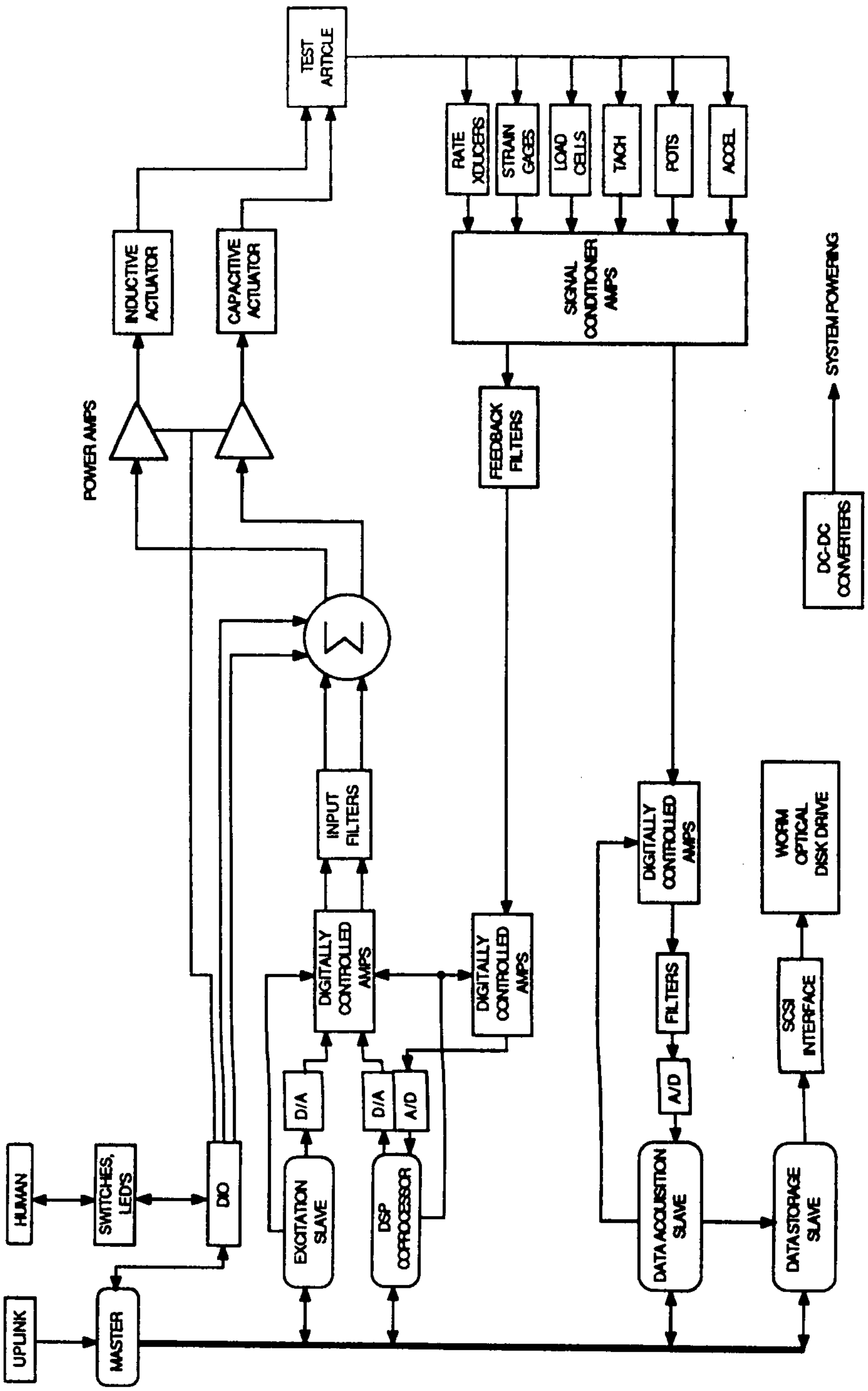


Figure 5.4.1 MACE Schematic Block Diagram

The dynamics calculations will be accomplished with a Digital Signal Processor (DSP) module. This will be a custom made STD card built around a TMS320C30 floating point processor or similar chip. The card will include 32 channels of 12 bit A/D conversion at 1 kHz maximum sampling rate per channel. 16 channels of 12 bit D/A conversion will also be supplied on the card. Dynamics processing will be performed locally, thus avoiding any significant use of the STD bus throughput.

The outputs of the Excitation Slave and DSP Coprocessor will be fed through a set of programmable gain amplifiers (Digitally Controlled Amps), to permit setting of the loop and input gains. Signals returning from the sensors will also pass through a set of Digitally Controlled Amps. All these amps will be controlled using the parallel output ports of the slave processors.

Note that separate A/D's, input filters, and programmable gain amps are devoted to acquiring data for storage. In order to examine higher response frequencies than those input to the test article, higher roll-off filters and faster sampling rates are required. Acquired data can be sent to the Data Storage Slave over the STD bus, or directly between cards using serial or parallel ports.

A listing of the components required to implement this design is given below.

5.4.3 Equipment List

Table 5.4.1 gives a summary of the components required to implement the reference design shown in the schematic block diagram (Figure 5.4.1). Several points should be kept in mind as this list is reviewed. Firstly, software development costs will be a major component of implementation cost. Secondly, the costs associated with design and development of custom circuitry cannot be accurately estimated at this time, as significant design effort may be applied to these circuits in order to meet power, size, and weight restrictions, while optimizing performance. This circuitry includes the Digitally Controlled Amps, The DSP Coprocessor and associated A/D's and D/A's, Data Acquisition Filters, Input Filters, Feedback Filters, the summation circuit, and the Signal Conditioner Amps.

The totals for this design are as follows:

- Cost: $69, 253. plus custom circuits
- Size: 753 cu. in. plus 23 slot STD card cage (approx. 600 cu. in.)
- Weight: 64 lbs, excluding test article and sensors

• Power: 170 Watts (with all four torque motors running)

Note that the power figure includes 15 W for 4 running torque motors, which may not be operated simultaneously. Also included in this figure is a loss of 23 W to power supply inefficiency. This assumed 80% efficiency of the DC-DC converters. Finally, 27 W was allocated to the Optical Disc Drive. This power figure is for the presently available ground version. A space qualified version is currently under development by the manufacturer, and is expected to have lower power consumption.

An entry is given titled"Miscellaneous", which is meant to include all other items required for fabrication of a ground prototype. This includes switches, cables, connectors, the metal support frame, STD card cage, fasteners, etc.

Table 5.4.1 Mace Equipment List

Item	Quantity	Description	Cost	Size	Weight	Power
Master	1	Ziatech ZT 8815 STD processor	$410.00	4.5 x 6.5" (1 STD slot)	6 oz	3.25 W typ.
DIO	1	Ziatech zSBX30 iSBX Digital input/ output card	$110.00	3 x 3.5" (1 STD slot)	~ 2 oz	1.2 W typ.
Excitation Slave	1	Ziatech ZT 8832 STD processor	$650.00	4.5 x 6.5" (1 STD slot)	6 oz	5 W typ.
Excitation D/A	1	Intel iSBX 328 Analog output card	$700.00	3 x 3.5" (1 STD slot)	~ 2 oz	2 W typ.
DSP Coprocessor Slave	1	Dynamics calculation	custom	4.5 x 6.5" (1 STD slot)	~ 8 oz	5 W est.
DSP A/D and D/A	32 A/D's 16 D/A's (maximum)	Analog I/O module	custom	4.5 x 6.5" (1 STD slot, maximum)	~ 8 oz	7.5 W est.
Data Acquisition Slave	2	Ziatech ZT 8832 STD processor	$650.00	2 x(4.5 x 6.5") (2 STD slots)	12 oz	10 W typ.
Data Acquisition A/D Converters	2	CDX AD 816 iSBX A/D card	$545.00	2 x(3 x 3.5") (2 STD slots)	3.2 oz	2 W typ.
Data Storage Slave	1	Ziatech ZT 8832 STD processor	$650.00	4.5 x 6.5" (1 STD slot)	6 oz	5 W typ.

Table 5.4.1 MACE Recommended Equipment List (Cont.)

Item	Quantity	Description	Cost	Size	Weight	Power
SCSI Interface	1	Ziatech zSBX 288 SCSI interface	$175.00	2.9 x 2.7" (1 STD slot)	1.6 oz	2 W typ.
WORM Drive	1	Optech SEL-2 Optical Disc Drive	$7,149.00	7 x 8 x11.4"	9.8 lb	27 W
Digitally Controlled Amps	3 sets 73 ch. max	Programmable gain amps	custom	3 x(4.5 x 6.5") (3 STD slots)	~1 lb	15 W est.
Input Filters	1 set 17 ch. max	Analog filters	custom	4.5 x 6.5" (1 STD slot)	8 oz	1.5 W est.
Data Acquisition Filters	1 set 32 ch. max	Anti-aliasing filters	custom	2 x(4.5 x 6.5") (2 STD slots)	1 lb	5 W est.
Feedback Filters	1 set 32 ch. max	Anti-aliasing filters	custom	2 x(4.5 x 6.5") (2 STD slots)	1 lb	5 W est.
Summation Circuit	1	Programmable signal adding, subtracting, etc.	custom	4.5 x 6.5" (1 STD slot)	8 oz	2 W est.
Power Amps	8 (estimated)	Power op-amps with heat sinks	$400.00	1.8 x 1.8 x 1.5" x 8	~ 1 lb	10 W est.
Inductive Actuators	4	Inland QT-7602	$21,064	8.5" dia x 1.3" x 4	29.2 lb	15 W typ. 67 W max

Table 5.4.1 MACE Recommended Equipment List (Cont.)

Item	Quantity	Description	Cost	Size	Weight	Power
Capacitive Actuators	unknown	Piezoelectric actuators embedded in structure	custom	N/A	N/A	0
Rate Transducers	9 (max)	ATA IETL-001 MHD angular rate transducers	$23,400	0.8"dia. x 0.6"H x 9	11 oz	2.2 W
Strain Gauges	15 (max)	Omega Y-series resistive foil type	$250.00	various (small)	~0	4 W max
Load Cells	1	Entran ELM-600A	$805.00	0.6" dia x 0.2" H	0.2 oz (5 gm)	300 mW
Pots	4	Precision potentiometers	$60.00	1" dia x 0.5"H x 4	~ 1 oz	40 mW typ.
Accelerometers	3	Sundstrand QA700 plus triaxial mount	$3,485.00	3.2 x 3.2 x 2.4" (size of triaxial mount)	1.2 lb	6.3 W
Signal Conditioners	1 set	Various amps and transducer powering (assume 32 AD 1B31 conditioner IC's)	$3,000	2 x(4.5 x 6.5") (2 STD slots)	1 lb	10 W est.
DC-DC Converters	4	2 x RWT 2405-12 1 x RWT 2405-15 1 x HCHR-300-128	$750.00	3.5 x 5.5 x 1.3" x 3 + 0.94 x 1 x0.38"	3 lb	23 W est. (assume 80% efficiency)

Table 5.4.1 MACE Recommended Equipment List (Cont.)

Item	Quantity	Description	Cost	Size	Weight	Power
Miscellaneous	--	Switches, cables, support frame, STD card cage, fasteners, connectors, etc.	$5,000.00	N/A	10 lb est.	--

Chapter Six: Management Plan

6.1 INTRODUCTION

6.1.1 Purpose

This chapter programatically outlines the methodology, schedule and budget for the development, certifcation and integration of the MACE experiment elements which constitute the MACE program. It is intended to be used as the project control and planning document as well as the repository for all information pertaining to the experiment and hardware development and testing.

6.1.2 Scope

This chapter is for use by the Project Science, Hardware Development and Certification/Integration teams in executing those tasks necessary to conduct research in micro-gravity. Data from this document is also intended to facilitate generation of other required documentation, such as the National Space Transportation System (NSTS) integration documentation.

6.1.3 Applicable Documentation

Safety Policy and Guidelines for Payloads Aboard the Space Transportation Systems	NHB 1700.7B
Payload Integration Plan for Middeck Payloads IDD for Middeck Payloads	NSTS-21000-IDD-MDK
Manned Systems Design Criteria Reliability and Quality Assurance	NHB 5300.1B

6.2 PROGRAM DEVELOPMENT

This section outlines and defines those activities required to facilitate the development of the individual experiments which constitute the MACE program.

6.2.1 Program Description

MACE is a program designed to provide investigative tools for experimentation and exploration into space structures and structural dynamics pertinant to planning permanent platforms in microgravity. MACE will consist of a programable Experiment Support Module (ESM) which occupies the space of one middeck locker and various test articles that are attached to the ESM. The ESM will excite the individual test articles and then record the dynamic response of the article. Many experiments utilizing MACE will employ feedback systems to control the test article as it is excited. This phase of MACE has far reaching implications in space structures design and management in micro-gravity.

6.2.2 Experiment Definition

The experiments within MACE may consist of a number of experiment protocols. Some protocols may involve only exciting the test article and recording its response in an unloaded micro-gravity environment. Other protocols may be designed to control the dynamic response of the test article using various types of integrated actuators that nullify the induced motion of the test article. Knowledge gained from the nature of this motion in a micro-gravity environment and the necessary systems and software to nullify such dynamic events will have direct application to space structures designs.

6.2.2.1 Studies

Studies are required to further define the systems, software and experimental requirements for conducting structures dynamics experimentation in the orbiter middeck. These studies include investigations into off-the-shelf hardware elements and systems, and computer algorythms that may be used to meet experiment goals. These studies are currently underway.

6.2.2.2 Testing

Testing is required to determine test article configuration and controller system architechture in order to address specific issues and design concerns adequately prior to experiment development design and activation. The testing plan will be implemented as dictated by results of studies of experimental systems.

6.2.3 Experiment Preliminary Design Review (PDR)

The experiment PDR is intended to be a formal review by the Project Science, Project Engineering and Integration personnel and serves as an aid in the definition phase

of experiment development. This review will be held after the experimental objectives, data parameters, and methodologies which will be employed during execution of the experiment have been defined. During the PDR the status of hardware development and integration and the prelimanary draft of the Experiment Document (ED) will be reviewed. Upon completion of the PDR, fabrication of prototype hardware or further studies and tests may be authorized. The PDR is a formal review and participation of representatives from all supporting organizations is highly desireable.

6.2.4 Experiment Critical Design Review (CDR)

The experiment CDR is the final review prior to baselining characteristics of the experiment design and serves as a final opportunity for the Project and Integrations team to review all aspects of the experiment. All studies and testing that may have a bearing on the experiment design must be completed and results interpreted by the completion of this review. During this review the ED is baselined and is placed under configuration control. The CDR is a formal review and participation of representatives from all supporting organizations is highly desireable.

6.3 HARDWARE DEVELOPMENT

6.3.1 Initial Requirements Review (IRR)

The IRR is conducted within the scope of applicable design critera as dictated by the NSTS and experiment requirements. The purpose of the IRR is to specify the flight hardware elements. If necessary, it is also intended to specify prototype hardware and the associated testing required to verify specific aspects of the hardware operation and function. This review occurs after the Experiment Definition to identify and baseline the hardware design and performance criteria.

6.3.2 Prototype I Testing

If required after the IRR, hardware performance specifications and behavior testing will be conducted on Prototype I hardware and software to verify and validate the experiment criteria. This fabrication, testing, modification and retesting is intended to identify and preclude any design deficiencies early in the design and development process. Prototype testing for MACE is planned for both the test articles and controller systems.

6.3.3 Hardware Preliminary Design Review

The MACE hardware PDR is a formal review and will include NSTS representatives as a precaution against prohibitive design deficiencies. This PDR occurs after sufficient Prototype I testing has assured a high probability of success for experiment execution by the MACE hardware. Drawings, specifications, manufacturing methods and other information is reviewed for completeness and functionality. Discrepancies are recorded on Review Item Dispositions (RID's) sheets and are submitted to the Project team. The RIDs are reviewed by the Project team and are accepted as written, accepted with modifcations or rejected. If accepted, comments are then incorporated into the design.

6.3.4 Prototype II Testing

Prototype II testing will be used to resolve any remaining issues or RID's concerning hardware element performance that have been raised at the hardware PDR. This testing data is then used at the hardware CDR to facilitate implementation of design changes and verify performance characteristics.

6.3.5 Hardware Critical Design Review

The hardware CDR is the final opportunity to investigate any concerns, comments or questions with regard to the hardware design or specifications prior to start of fabrication. All comments and RID's must be dispositioned as before at the PDR. All testing data will be reviewed and evaluated. In a manner similar to the hardware PDR, the CDR is a formal review and should include NSTS representation.

6.3.6 Fabrication

Fabrication will be authorized only after the successful completion of the CDR. Fabrication will be conducted in conformance with NHB 5300.1B using appropriate inspection and control procedures.

6.3.7 Acceptance Testing

In the process of fabrication and/or at the end of production, as required, testing will be performed on hardware elements to ensure they meet design and performance specifications. Upon successful completion of acceptance testing, the hardware elements will then be accepted and considered flight hardware as specified in NHB 5300.1B.

6.3.8 Design Certification Review (DCR)

The DCR will be held after the completion of all fabrication and acceptance testing. The purpose of the DCR is to review and disposition any remaining open items, verify the status of acceptance tests and to formally certify the design as sufficient to meet experiment and NSTS requirements for flight hardware. At the completion of the DCR, the hardware is considered flight and will be handled per the applicabe NSTS requirements.

6.4. CERTIFICATION TESTING

Certification testing will be performed to certify the flight hardware after the successful completion of the DCR. The test plan will be generated in accordance with NSTS-21000-IDD-MDK (IDD), as applicable, and will include EMI/EMC, Offgas/Flammability, Vibration/Loads, Thermal analyses. If testing is not feasible or is superfluous, engineering analyses will be performed as stated in the applicable guidelines to demonstrate the proper hardware performance and safety.

6.4.1 Electromagnetic Interference/ Electromagnetic Compatibility

The electromagnetic interference and electromanetic compatibility (EMI/EMC) test will be performed at an independent military certified laboratory. Procedures and testing levels will procede as outlined in the middeck IDD. The project will assume all responsiblity for testing and test results. Test results will be transmitted to NSTS for review and approval.

6.4.2 Offgas Testing

Offgas testing will be performed by STS using NHB 8080 procedures to certify the hardware for crew compartment areas. Following successful completion of the offgas testing, a certification will be issued by NSTS.

6.4.3 Vibration Testing

The vibration testing will be performed at an independent military certified laboratory. Procedures and testing levels will procede as outlined in the middeck IDD. The project will assume all responsiblity for testing and test results. Test results will be transmitted to NSTS for review and approval.

6.4.4 Thermal Analysis and Testing

Thermal analyses will be performed on the entire experiment compliment per the guidlines of the IDD. Should these analyses prove insufficient to meet NSTS requirements, a thermal testing protocol will be conducted using a military independant testing laboratory and the test results will be submitted to NSTS for review and approval.

6.6. PAYLOAD INTEGRATION

6.6.1 Experiment Document (ED)

An ED will be generated to control and outline the mission requirements allocated to MACE. The ED is an internal document, but is formatted to closely follow the required NSTS documentation for easy implementation and integration. The outline of the ED is as follows:

6.6.1.1 Introduction

- describes document's function, purpose, scope and other applicable documentation.

6.6.1.2 Experiment Overview

- describes experiment objectives, history, rationale, project structure, etc.

6.6.1.3 Experiment Data Objectives

•(self explanatory)

6.6.1.4 Flight Equipment and Accomodations

•Lists by part number

a) experiment apparatus

b) stowage items

c) power cable

d) data storage (tapes, discs etc)

Data from this section will be used to generate PIP Annex 6.

6.6.1.5 Mission Scenario

•figure 6.1 shows overall flow

6.6.1.6.1 Preflight Operations

6.6.1.6.2 In Flight Operations

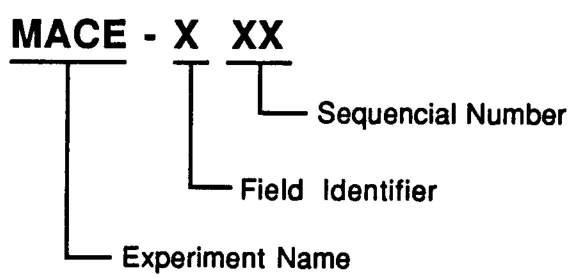
6.6.1.6.3 Post Flight Operations

Data from the mission scenario will be used to generate parts of the Payload Integration Plan (PIP) and Annex 2 and 3.

6.6.1.6 Ground Processing Requirements

This section outlines the facilities, equipment, supplies, special services and any special requirements and constraints involved with processing the experiment prior to flight.

Requirements for facilities, equipment, supplies, special services, and special requirements/constraints will be identified in the following manner:



Field Identifier Key

0	Facilities
1	Equipment
2	Supplies
3	Special Requirements/Constraints
4	Special Services
5	Landing Site or CLS Unique Requirements
6	Contingency Requirements

Data from this section will be used to generate PIP Annex 8.

6.6.1.7 Integration Requirements

This section outlines requirements and constraints during the entire integration process into the NSTS. This includes requirements for interfaces verification test(s) and their associate specifications and criteria. Data from this section will be used to generate PIP Annex 9.

6.6.1.8 Flight Operations

This section identifies all procedures, methods and malfunction procedures required to successfully perform the experiement on orbit. Data from this section will be used to generate PIP Annex 3.

6.6.1.9 Crew Training

This section of the ED identifies the crew training plans, both for familiarization and proficiency, to enable the crew to successfully operate the experiments and resolve any inflight problems. Data from this section will be used to generate PIP Annex 7.

6.6.2 Payload Integration Plan (PIP)

The PIP is the controlling document between the payload element and NSTS for resources allocated for each MACE experiment. The ED will be used, along with other information as needed to negotiate and generate the PIP.

6.6.2.1 PIP Annex 1 Payload Data

This annex of the PIP describes and controls the physical aspects of the flight experiment and will be generated by NSTS with inputs from the project team.

6.6.2.2 PIP Annex 2 Experiment Operations Scheduling

This annex of the PIP describes and controls the scheduling issues of the flight experiment and will be generated by NSTS with inputs from the project team.

6.6.2.3 PIP Annex 3 Crew Procedures

This annex of the PIP describes and controls the crew operations and malfunction procedures for execution of the experiment and will be generated by NSTS with inputs from the project team.

6.6.2.4 PIP Annex 6 Crew Compartment

This annex of the PIP describes and controls the experiment hardware and stowage items to be flown in support of the experiment and will be generated by NSTS with inputs from the project team.

6.6.2.5 PIP Annex 7 Crew Training

This annex of the PIP describes and controls the training requirements for familiarization and crew proficiency for the experiment and will be generated by NSTS with inputs from the project team.

6.6.2.6 PIP Annex 8 Launch Site Support

This annex of the PIP describes and controls the experiment processing requirements at Kennedy Space Center and the landing site in support of the experiment and will be generated by NSTS with inputs from the project team.

6.6.2.7 PIP Annex 9 Integration Verification

This annex of the PIP describes and controls the payload to NSTS integration verification requirements at Kennedy Space Center in support of the experiment and will be generated by NSTS with inputs from the project team.

6.6.3 Phase Safety Review Process

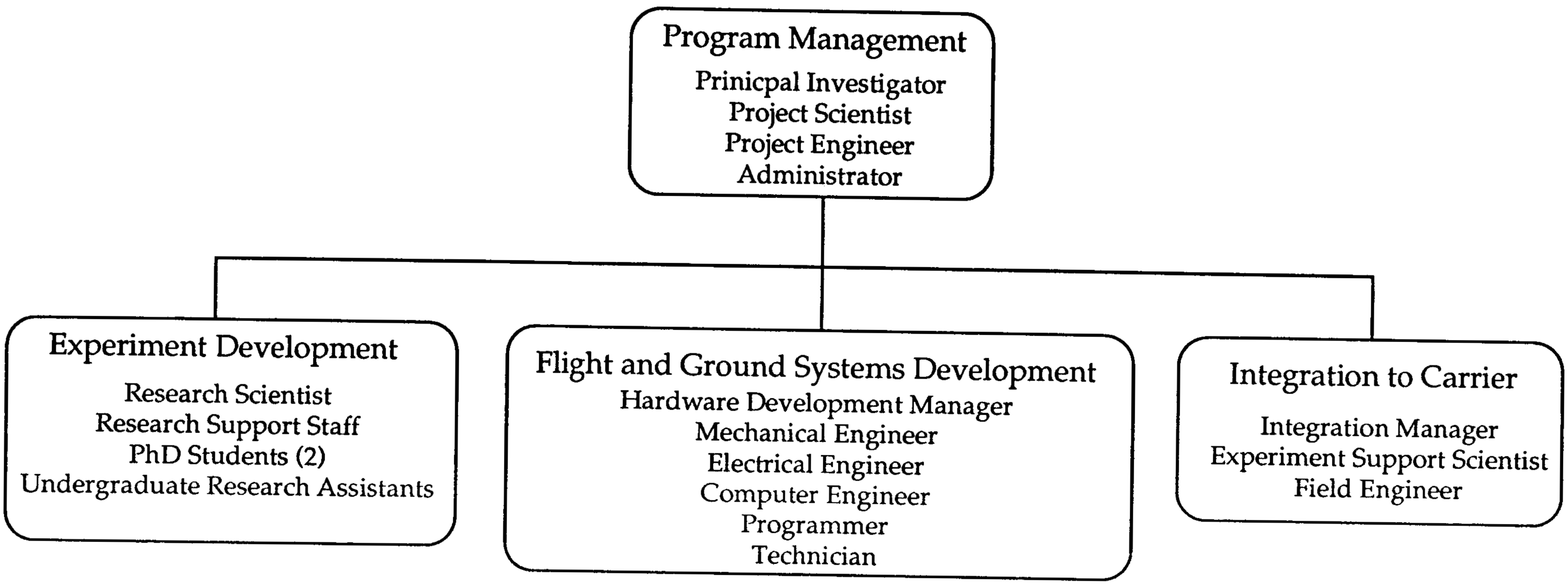
The phase safety review process will be conducted in four stages, as outlined in JSC 138030. In addition, when applicable, JSC/NSTS Materials, Battery, Toxicology and Safety personnel will be consulted as a design resource in the absence of such a capability at the Mission Management Center for MACE. JSC/NSTS guidelines will be used exclusively as the controlling criteria for safety design implementation and deficiencies resolution.

6.6.4 Engineering Analyses

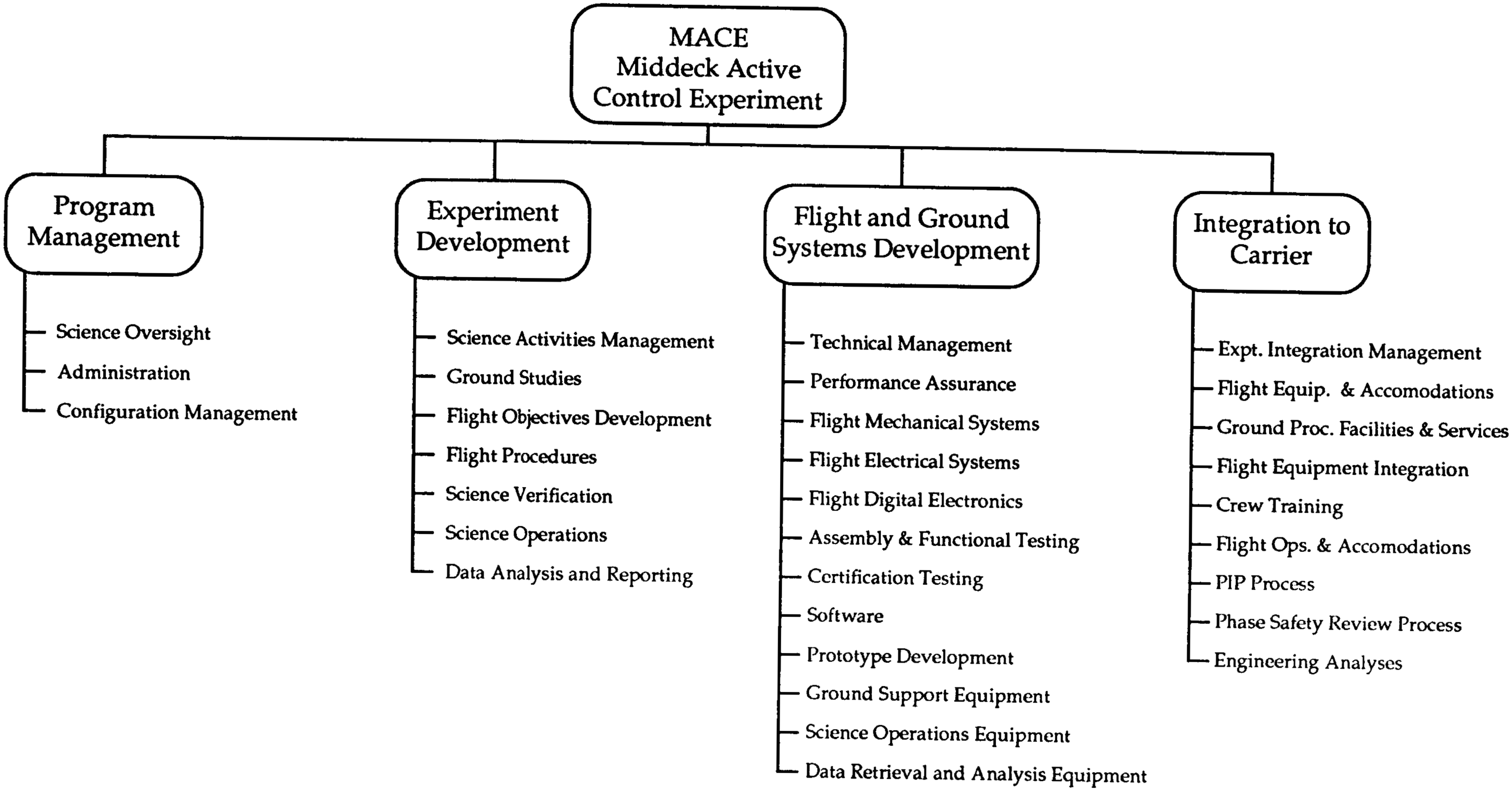
Analyses will be conducted, as dictated by the appropriate NSTS requirement, for thermal and loads properties of the experiment and submitted to NSTS for use in mission integration and planning activities. Where analyses are determined to be insufficient, testing per the applicable NSTS requirement will be conducted. Results will be submitted to NSTS for review and approval.

6.7 WORK BREAKDOWN SCHEDULE

On the following pages, a work breakdown structure for the MACE program leading up to the first flight of the reference test article is presented.



Project Organization for MACE



Work Breakdown Structure for MACE

Work Breakdown Structure

For purposes of program management, the work to be performed in the MODE program is divided into four categories:

1. Program Management
2. Experiment Development
3. Flight and Ground Systems Development
4. Integration to Carrier

These categories are further divided as shown in the attached figure. The full work breakdown structure is contained in the following outline:

1. Program Management

1.1. Science Oversight

1.2. Administration
1.2.1. Contracts
1.2.2. Personnel
1.2.3. Procurement
1.2.4. Travel

1.3. Configuration Management

continued ...

Work Breakdown Structure (cont.)

2. Experiment Development

2.1. Science Activities Management
2.2. Ground Studies
2.2.1. Test Article Refinement
2.2.2. Prototype I Detailed Design
2.2.3. Prototype I Testing
2.2.4. Dynamic Modelling
2.2.5. Dynamic Testing
2.2.6. Control Algorithm Formulation
2.2.7. Control Algorithm Testing
2.2.8. Prototype I Evaluation
2.2.9. Prototype II Testing and Evaluation

2.3. Flight Objectives Development
2.3.1. Detailed Science Requirements
2.3.2. Flight Experiment Plan
2.3.3. Detailed Inflight Data Objectives

2.4. Flight Procedures Development
2.4.1. Nominal Flight Procedures
2.4.2. Nominal Ground Procedures
2.4.3. Contingency Procedures
2.4.4. Malfunction Procedures

2.5. Science Verification
2.5.1. Experiment Configurability
2.5.2. Actuation Capabilities
2.5.3. Test Article Dynamics
2.5.4. Data Quality
2.5.5. Feedback Control Capabilities
2.5.6. Expt. Ops and Data Analysis End-to-End Test

2.6. Science Operations
2.6.1. Plan for Science Ops during Flight
2.6.2. Preparations and Simulations
2.6.3. Science Ops during Flight

2.7. Data Analysis and Reporting
2.7.1. Data Management
2.7.2. Data Analysis Development
2.7.3. Data Analysis during Flight
2.7.4. Postflight Data Recovery
2.7.5. Postflight Data Analysis
2.7.6. Evaluation and Reporting

continued ...

Work Breakdown Structure (cont.)

3. **Flight and Ground Systems Development**

3.1. Technical Management
3.1.1. Systems Engineering
3.1.2. Flight Resources Management
3.1.2.1. Power
3.1.2.2. Weight
3.1.2.3. Volume
3.1.2.4. Crew Timeline
3.1.3. Structural Analysis
3.1.4. Thermal Analysis

3.2. Performance Assurance
3.2.1. Quality Assurance
3.2.2. Reliability Assurance
3.2.3. Safety

3.3. Flight Mechanical Systems
3.3.1. Test Article
3.3.2. Actuators and Sensors (mechanical)
3.3.3. Experiment Support Module
3.3.4. Accommodation to Middeck Lockers

3.4. Flight Electrical Systems
3.4.1. Power
3.3.2. Actuators and Sensors (electrical)
3.4.3. Actuator Signal Conditioning
3.4.4. Sensor Signal Conditioning

3.5. Flight Digital Electronics
3.5.1. Master Processor and Bus
3.5.1.1. Master Processor
3.5.1.2. Bus
3.5.1.3. Digital I/O
3.5.1.4. External Communications
3.5.2. Excitation Subsystem
3.5.3. Digital Feedback Subsystem
3.5.3.1. DSP Coprocessor
3.5.3.2. Feedback Signal Acquisition
3.5.3.2. Feedback Control Output
3.5.4. Data Acquisition Subsystem
3.5.5. Data Storage Subsystem
3.5.5.1. Data Storage Slave
3.5.5.2. SCSI
3.5.5.3. WORM optical drive

3.6. Assembly and Functional Testing

continued ...

Work Breakdown Structure (cont.)

3.7.	Certification Testing
3.7.1.	Electromagnetic Interference/Compatibility
3.7.2.	Offgas Testing
3.7.3.	Vibration Testing
3.7.4.	Thermal Testing
3.8.	Software
3.8.1.	Software Management and Control
3.8.2.	Software Validation
3.8.3.	Flight Software Development
3.8.4.	Science Operations Software
3.8.5.	Ground Data Analysis Software
3.9.	Prototype Development
3.9.1.	Prototype I Design
3.9.2.	Prototype I Fabrication
3.9.3.	Prototype I Engineering Testing
3.9.4.	Prototype II Design
3.9.5.	Prototype II Fabrication
3.9.6.	Prototype II Engineering Testing
3.10.	Ground Support Equipment (GSE)
3.10.1.	Mechanical GSE
3.10.2.	Electrical GSE
3.10.3.	Digital Electronics GSE
3.11.	Science Operations Equipment
3.11.1.	Digital Data
3.11.2.	Voice
3.11.3.	Video
3.12.	Data Retrieval and Analysis Equipment
3.12.1.	Digital Data
3.12.2.	Video

continued ...

Work Breakdown Structure (cont.)

4. Integration to Carrier

4.1. Experiment Integration Management

4.2. Flight Equipment and Accommodations
4.2.1. Experiment Complement
4.2.2. Equipment Stowage
4.2.3. External Cables (power, video)
4.2.4. Data Storage Media

4.3. Ground Processing Facilities and Services

4.4. Flight Equipment Integration
4.4.1. Equipment Delivery and Acceptance
4.4.2. Functional Testing
4.4.3. Interface Testing

4.5. Crew Training
4.5.1. Astronaut Office Experiment Support Group
4.5.2. Experiment Familiarization
4.5.3. Procedures Training
4.5.4. Proficiency Training

4.6. Flight Operations and Accommodations

4.7. Payload Integration Plan (PIP) Process
4.7.1. Annex 1: Payload Data
4.7.2. Annex 2: Experiment Operations Scheduling
4.7.3. Annex 3: Crew Procedures
4.7.4. Annex 6: Crew Compartment
4.7.5. Annex 7: Crew Training
4.7.6. Annex 8: Launch and Landing Site Support
4.7.7. Annex 9: Integration Verification

4.8. Phase Safety Review Process
4.8.1. Phase 0
4.8.2. Phase I
4.8.3. Phase II
4.8.4. Phase III
4.8.5. Phase IV

4.9. Engineering Analyses
4.9.1. Thermal Analysis
4.9.2. Loads Analysis
4.9.3. Electromagnetic/Radio Frequency

End of Work Breakdown Structure.

Personnel

The personnel required to carry out the MACE program are identified according to the work breakdown structure of the previous section. Their level of involvement is indicated for each phase of the program. (For an explanation of the phases see section 5D.)

	Phase B	Phase C/D/E
1. Program Management		
Principal Investigator	20%	20%
Project Scientist	50%	50%
Project Engineer	100%	100%
Administrator	5%	5%
2. Experiment Development		
Research Scientist	50%	25%
Research Support Staff	100%	50%
Graduate Research Assistants (2)	200%	200%
Undergraduate Research Assistants		
3. Flight and Ground Systems Development		
Hardware Development Manager	35%	50%
Mechanical Engineer	0%	100%
Electrical Engineer	0%	50%
Digital Electronics Engineer	50%	150%
Programmer	20%	50%
Technician	20%	100%
4. Integration to Carrier		
Integration Manager	10%	35%
Experiment Support Scientist	25%	35%
Field Engineer	0%	50%

Task Assignments from Work Breakdown Structure

Principal Investigator
1. Program Management
1.1. Science Oversight

Project Scientist
1.1. Science Oversight
2.1. Science Activities Management

Project Engineer
1.3. Configuration Management
3.2. Performance Assurance
3.2.1. Quality Assurance
3.2.2. Reliability Assurance
3.2.3. Safety

Administrator
1.2. Administration
1.2.1. Contracts
1.2.2. Personnel
1.2.3. Procurement
1.2.4. Travel

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Research Scientist assisted by:
Research Support Staff, Graduate Research Assistants, and Undergraduates

2.2. Ground Studies
2.2.1. Test Article Refinement
2.2.2. Prototype I Detailed Design
2.2.3. Prototype I Testing
2.2.4. Dynamic Modelling
2.2.5. Dynamic Testing
2.2.6. Control Algorithm Formulation
2.2.7. Control Algorithm Testing
2.2.8. Prototype I Evaluation
2.2.9. Prototype II Testing and Evaluation
2.3. Flight Objectives Development
2.3.1. Detailed Science Requirements
2.3.2. Flight Experiment Plan
2.3.3. Detailed Inflight Data Objectives
2.5. Science Verification
2.5.1. Experiment Configurability
2.5.2. Actuation Capabilities
2.5.3. Test Article Dynamics
2.5.4. Data Quality
2.5.5. Feedback Control Capabilities
2.5.6. Expt. Ops and Data Analysis End-to-End Test
2.7. Data Analysis and Reporting
2.7.1. Data Management
2.7.2. Data Analysis Development
2.7.3. Data Analysis during Flight
2.7.4. Postflight Data Recovery
2.7.5. Postflight Data Analysis
2.7.6. Evaluation and Reporting
3.8. Software
3.8.4. Science Operations Software
3.8.5. Ground Data Analysis Software
3.9. Prototype Development
3.9.1. Prototype I Design
3.9.2. Prototype I Fabrication

in conjunction with Experiment Support Scientist:

2.4. Flight Procedures Development
2.4.1. Nominal Flight Procedures
2.4.2. Nominal Ground Procedures
2.4.3. Contingency Procedures
2.4.4. Malfunction Procedures
2.6. Science Operations
2.6.1. Plan for Science Ops during Flight
2.6.2. Preparations and Simulations
2.6.3. Science Ops during Flight

in conjunction with Digital Electronics Engineer:

3.11. Science Operations Equipment
3.11.1. Digital Data
3.12. Data Retrieval and Analysis Equipment
3.12.1. Digital Data
3.12.2. Video

Hardware Development Manager

3. Flight and Ground Systems Development
3.1. Technical Management
3.1.1. Systems Engineering
3.1.2. Flight Resources Management
3.1.2.1. Power
3.1.2.2. Weight
3.1.2.3. Volume
3.10. Ground Support Equipment (GSE)
3.11. Science Operations Equipment
3.12. Data Retrieval and Analysis Equipment

assisted by the Field Engineer:

3.7. Certification Testing
3.7.1. Electromagnetic Interference/Compatibility
3.7.2. Offgas Testing
3.7.3. Vibration Testing
3.7.4. Thermal Testing
4.2. Flight Equipment and Accommodations
4.2.1. Experiment Complement
4.2.2. Equipment Stowage
4.2.3. External Cables (power, video)
4.2.4. Data Storage Media
4.4. Flight Equipment Integration
4.4.1. Equipment Delivery and Acceptance
4.4.2. Functional Testing
4.4.3. Interface Testing

assisted by the Digital Electronics Engineer and Programmer:

3.8. Software
3.8.1. Software Management and Control
3.8.2. Software Validation

assisted by the ME, EE, and DEE:

3.9. Prototype Development
3.9.3. Prototype I Engineering Testing
3.9.4. Prototype II Design
3.9.5. Prototype II Fabrication
3.9.6. Prototype II Engineering Testing

Mechanical Engineer

3.3.	Flight Mechanical Systems	
3.3.1.		Test Article
3.3.2.		Actuators and Sensors (mechanical)
3.3.3.		Experiment Support Module
3.3.4.		Accommodation to Middeck Lockers
3.9.	Prototype Development	
3.9.3.		Prototype I Engineering Testing
3.9.4.		Prototype II Design
3.9.5.		Prototype II Fabrication
3.9.6.		Prototype II Engineering Testing
3.10.	Ground Support Equipment (GSE)	
3.10.1.		Mechanical GSE
4.9.	Engineering Analyses	
4.9.1.		Thermal Analysis
4.9.2.		Loads Analysis

Electrical Engineer

3.4.	Flight Electrical Systems	
3.4.1.		Power
3.3.2.		Actuators and Sensors (electrical)
3.4.3.		Actuator Signal Conditioning
3.4.4.		Sensor Signal Conditioning
3.9.	Prototype Development	
3.9.3.		Prototype I Engineering Testing
3.9.4.		Prototype II Design
3.9.5.		Prototype II Fabrication
3.9.6.		Prototype II Engineering Testing
3.10.	Ground Support Equipment (GSE)	
3.10.2.		Electrical GSE
3.11.	Science Operations Equipment	
3.11.2.		Voice
3.11.3.		Video
4.9.	Engineering Analyses	
4.9.3.		Electromagnetic/Radio Frequency

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Digital Electronics Engineer

3.5.	Flight Digital Electronics
3.5.1.	Master Processor and Bus
3.5.1.1.	Master Processor
3.5.1.2.	Bus
3.5.1.3.	Digital I/O
3.5.1.4.	External Communications
3.5.2.	Excitation Subsystem
3.5.3.	Digital Feedback Subsystem
3.5.3.1.	DSP Coprocessor
3.5.3.2.	Feedback Signal Acquisition
3.5.3.2.	Feedback Control Output
3.5.4.	Data Acquisition Subsystem
3.5.5.	Data Storage Subsystem
3.5.5.1.	Data Storage Slave
3.5.5.2.	SCSI
3.5.5.3.	WORM optical drive
3.8.	Software
3.8.1.	Software Management and Control
3.8.2.	Software Validation
3.9.	Prototype Development
3.9.3.	Prototype I Engineering Testing
3.9.4.	Prototype II Design
3.9.5.	Prototype II Fabrication
3.9.6.	Prototype II Engineering Testing
3.10.	Ground Support Equipment (GSE)
3.10.3.	Digital Electronics GSE

in conjunction with Research Staff:

3.11.	Science Operations Equipment
3.11.1.	Digital Data
3.12.	Data Retrieval and Analysis Equipment
3.12.1.	Digital Data

Programmer

3.8.	Software
3.8.1.	Software Management and Control
3.8.2.	Software Validation
3.8.3.	Flight Software Development
3.8.4.	Science Operations Software

Technician

3.6.	Assembly and Functional Testing
3.9.	Prototype Development
3.9.5.	Prototype II Fabrication

Integration Manager

4. Integration to Carrier
4.1. Experiment Integration Management
4.6. Flight Operations and Accommodations
4.7. Payload Integration Plan (PIP) Process
4.7.1. Annex 1: Payload Data
4.7.2. Annex 2: Experiment Operations Scheduling
4.7.3. Annex 3: Crew Procedures
4.7.4. Annex 6: Crew Compartment
4.7.5. Annex 7: Crew Training
4.7.6. Annex 8: Launch and Landing Site Support
4.7.7. Annex 9: Integration Verification
4.8. Phase Safety Review Process
4.8.1. Phase 0
4.8.2. Phase I
4.8.3. Phase II
4.8.4. Phase III
4.8.5. Phase IV

in conjunction with Hardware Development Manager:

4.9. Engineering Analyses

in conjunction with Field Engineer:

4.2. Flight Equipment and Accommodations
4.3. Ground Processing Facilities and Services
4.4. Flight Equipment Integration
4.6. Flight Operations and Accommodations

Experiment Support Scientist

2.4.	Flight Procedures Development
2.4.1.	Nominal Flight Procedures
2.4.2.	Nominal Ground Procedures
2.4.3.	Contingency Procedures
2.4.4.	Malfunction Procedures
2.6.	Science Operations
2.6.1.	Plan for Science Ops during Flight
2.6.2.	Preparations and Simulations
2.6.3.	Science Ops during Flight
3.1.2.	Flight Resources Management
3.1.2.4.	Crew Timeline
4.5.	Crew Training
4.5.1.	Astronaut Office Experiment Support Group
4.5.2.	Experiment Familiarization
4.5.3.	Procedures Training
4.5.4.	Proficiency Training

Field Engineer

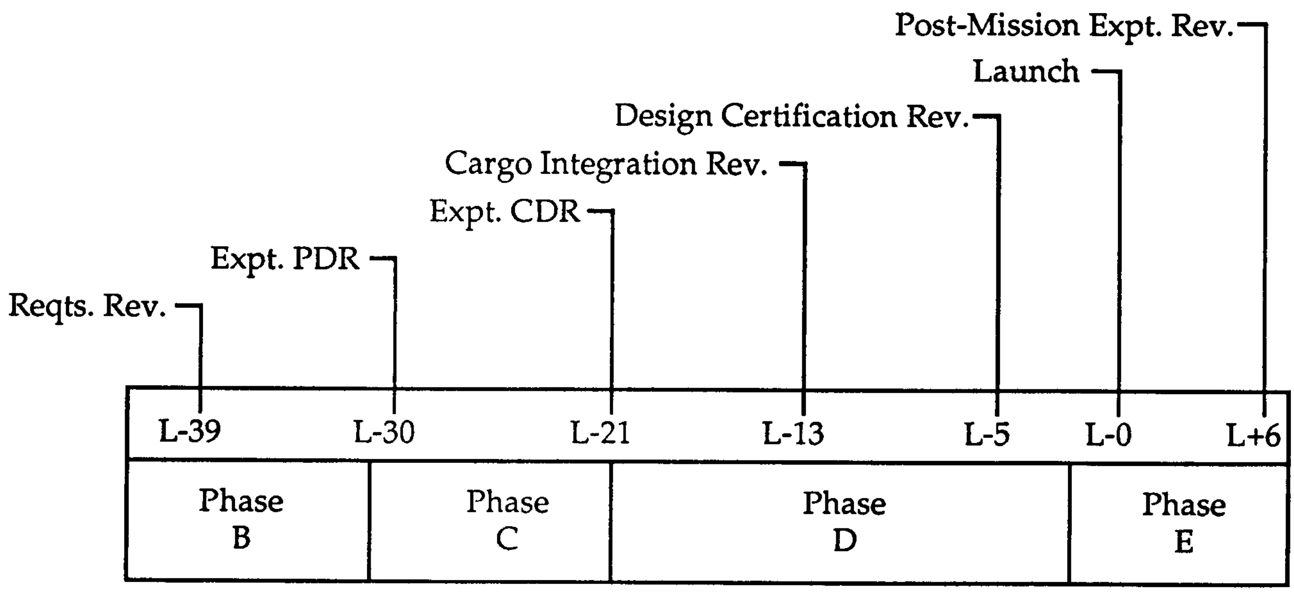
3.6.	Assembly and Functional Testing
3.7.	Certification Testing
3.7.1.	Electromagnetic Interference/Compatibility
3.7.2.	Offgas Testing
3.7.3.	Vibration Testing
3.7.4.	Thermal Testing
4.2.	Flight Equipment and Accommodations
4.2.1.	Experiment Complement
4.2.2.	Equipment Stowage
4.2.3.	External Cables (power, video)
4.2.4.	Data Storage Media
4.3.	Ground Processing Facilities and Services
4.4.	Flight Equipment Integration
4.4.1.	Equipment Delivery and Acceptance
4.4.2.	Functional Testing
4.4.3.	Interface Testing

6.8 SCHEDULE

The attached figures show the experiment development and integration schedules for MACE.

6.9 BUDGET

The following tables indicate the hardware and manpower costs associated with establishing the MACE program and flying the Reference MACE Multibody Test Article. Only the hardware necessary for the first flight of the MACE test article is included. The complete ESM hardware and development cost is included, with the exception that the data downlink system development costs are not included in the quoted price.



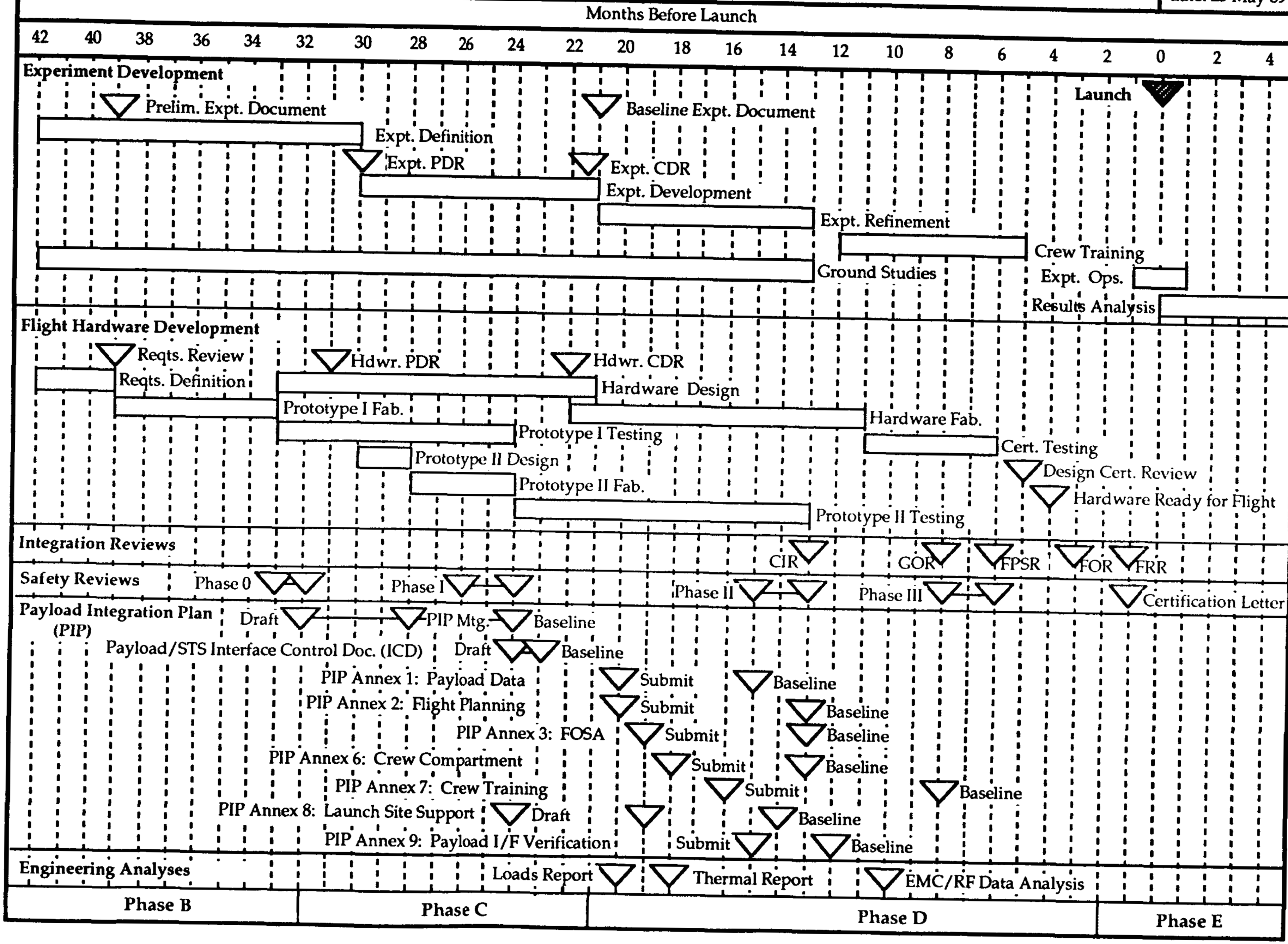
Schedule Summary for MACE

file: MACE-Schedule

MACE: Middeck Active Control Experiment

Experiment Development Schedule

resp: A. Arrott
date: 25 May 89



MACE Budget Summary

	Phase B	Phase C/D/E
Salaries and Wages	174,431	496,343
Employee Benefits	69,772	198,537
Operating Costs		
Materials and Services	27,000	42,000
Travel	9,750	86,840
Computation	21,600	66,600
Office supplies, telephone, postage	2,400	7,400
Report Costs	1,560	9,620
Machine Shop	41,000	71,000
Subcontract (no MIT overhead)		
Salaries and Wages	184,828	1,605,344
Materials and Services	107,000	1,900,000
Travel	12,230	142,000
Indirect Costs	218,933	616,354
Total	870,504	5,242,038
Total for Project		6,112,542

Chapter Seven: Conclusions

A rationale to determine which structural experiments (open or closed-loop, ground or orbit-based) are sufficient to verify the design of structures employing Controlled Structures Technology was derived. It was demonstrated the open-loop experiments are not sufficient to demonstrate stability and performance of the closed-loop plant. Furthermore, significant differences between the ground and orbit environments, arising from the presence of singular perturbations or substantial regular perturbations on the various structural parameters, make it likely that ground-based tests alone would lead to incorrect models of the structure. On-orbit open-loop tests need to be carried out to determine the existence of these perturbations. If they are found, then on-orbit closed-loop tests are absolutely required. If they are not found, on-orbit closed-loop tests may still be carried if the additional cost involved in testing a closed-loop system is small, or if the performance metric that is used by the system is only available on-orbit.

A survey of proposed NASA missions was undertaken to identify candidate test articles for use in MACE. The survey revealed that potential test articles could be classified into one of three roles: *development*, *demonstration*, and *qualification*, depending on the maturity of the technology and the mission the structure must fulfill. A set of criteria was derived that allowed determination of which role a potential test article fulfilled. These criteria were applied to a set of five test articles drawn from a survey of future NASA or DoD missions. From this process, a development test article consisting of a multibody platform (MBP) was selected.

A scaling analysis was performed on the entire closed-loop system and revealed no fundamental problems in scaling results obtained on a test article in the STS middeck to a full size structure. Most structural parameters, disturbances, and performance metrics were found either to scale appropriately or to be modellable. The exceptions were gravity gradient torques, which do not scale due to the inability to control the amount of gravity felt by a structure, and certain performance metrics such as surface tolerances on optical instruments, which cannot be adequately scaled since the ability to vary electro-magnetic waves is limited.

A review of the capabilities and limitations of the STS middeck was conducted. Power, volume and size constraints were identified, as well as limitations on STS-provided

services, such as data downlink. Of all the constraints, power consumption (115 W per experiment) was found to drive the design of the MACE experiment.

A reference design for the MACE test article was presented. It consisted of a multibody platform with a 1.5 m segmented tubular bus. Two pointing/tracking payloads are located at both ends of the structure. Universal joints provide for the electrical and mechanical connections between the various tubular segments and the payloads. The modularity of the design allows different payloads, actuators and sensors to be connected with minimal effort, and permits the baseline configuration to be changed and to evolve to more complex structures.

A test sequence was developed which addresses the two fundamental problems faced by multibody platforms: performance in the presence of structure-borne disturbances and performance in the presence of other actively controlled payloads. The designed payload will be sequentially used in angular pointing, tracking, and random input modes in order to examine both of these issues. The orbit tests would be duplicated on the ground during both the pre- and post-flight phases of the program. This ground test program is required in order to obtain the maximum amount of scientific return from the STS flights.

Computing requirements for running typical closed-loop controllers were determined, and various computer configurations were studied. An STD-bus master/slave architecture was selected as the best candidate, due to the wide availability of "off-the-shelf" specialized cards, its low power, size and weight requirements, and the familiarity that exist with such a system both at MIT and at the subcontractor. The various components required to manufacture the structure were identified, and a survey of commercially available products revealed no unexpected difficulty in obtaining satisfactory instrumentation.

A management plan was established for the remainder of the program. The team was broken into three separate areas: experiment development, flight and ground systems development, and integration to the carrier. A work breakdown structure for the program was developed and specific jobs and responsibilities have been assigned to each member of the team. Procedures for configuration control, fiscal control, and safety, reliability and quality assurance have been developed. Finally, a launch delay work-around plan was established for both MIT and the subcontractor.

A three and one-half schedule is proposed for the entire MACE program, leading from the Phase B ground-test development to the post-flight analysis. Interaction with the NASA Johnson Space Center integration staff, as well as with the Astronaut office in order

to establish crew training procedures, has already begun, and is reflected in the schedule. The total cost of the program up until the end of the post-flight analysis phase is $6 million. This cost reflects the requirement that, in order for MACE to achieve a valuable scientific return, it must be coupled to a vigorous ground test program, whose cost is included in the above figure.

Appendix A:
Scale Model of Remote Manipulator System

A.1 MOTIVATION

There is a need to develop flight *qualification* procedures for qualifying future CST structures. Once developed, these procedures can be implemented to define the operational envelope. The STS Remote Manipulator System (Fig. A.1.1) is a CST structure that has flown and will fly on numerous occasions. However, its operational envelope is restricted because of Orbiter safety concerns. In addition, the construction of the Space Station will require the RMS to position payloads larger than those for which it was originally designed. A scale model of the RMS might prove useful for the qualification of the system for this mission.

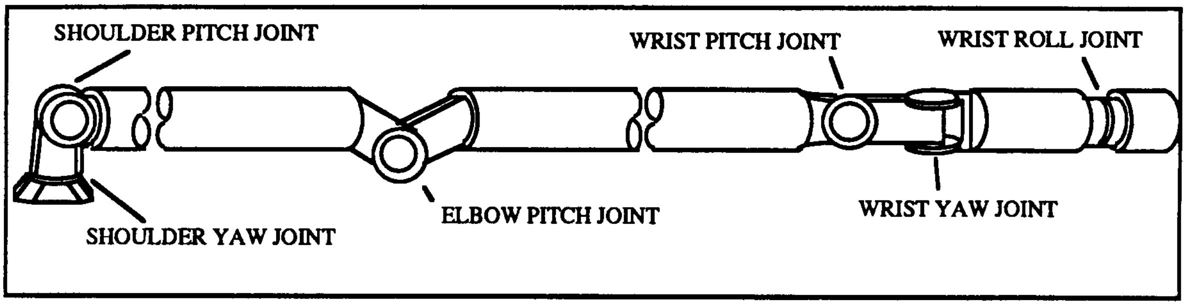


Figure A.1.1 Space Shuttle Remote Manipulator System (RMS)

Decreasing the reorientation response time and increasing the maneuvering rates of the RMS carries with it implications on safety. If the RMS achieves a high maneuver rate and control is lost, either the RMS could damage the Shuttle or itself. There is a clear need to test the procedures, to be used to increase the performance of the RMS, on a test article resembling the RMS and in an environment similar to that in which the RMS operates. This might provide a more safe and cost effective means for identifying potential problems and solutions prior to actual testing on the RMS. In other words, it could help map out the flight hardware performance envelope without risking damage to actual, full scale RMS or Shuttle.

A.2 TEST ARTICLE CONFIGURATION

Since the RMS is fifty feet in length, and the middeck provides ten feet diagonally across the middeck locker wall, the scale factor would have to be approximately 1/7.5. A

problem arises with regard to the scaling of the frequencies. Since the RMS is controlled by the astronauts through a joystick, it is desirable to keep the first fundamental frequency of the scaled test article near the frequency of the actual, full-scale RMS. In this way, the visual cues and response times of the astronauts will be maintained. Replica scaling, however, implies a scaling of the frequencies of the scaled article yielding higher frequencies for the smaller structure. A possibility for accommodating this problem is to use hybrid scaling where the length is scaled so that the structure fits in the middeck (< 1/7.5) and the time scale is maintained equal to unity. The frequencies of the test article could be maintained by using a different material for the links or incorporating additional springs in the joints. Another possibility is to use a "scaled human", *i.e.*, electronic commands representative of typical human commands and reactions, but scaled to the appropriate level. Table A.2.1 shows the various parameter values for different scaling methods.

The numbers show that while replica scaling has acceptable values, the changes in frequencies would make it unacceptable to be used with a human in the control loop. The multiple scaling when the time scale is maintained equal to unity keeps the frequencies the same but the mass of the test article is the same as the full scale and is therefore innappropriate for the middeck. A scaling method where the time scale is equal to 0.4 provides a compromise in that the frequencies are maintained close to their original values (by a factor of 2.5) and the geometric parameters are scaled so as to fit in the middeck (the total mass is approximately 60 lbs). The maximum amount allowed for storage in one middeck locker is 100 lbs, which would imply a time scale factor of 0.455.

A.2.1 Computers and Instrumentation

Without incorporating the wrist yaw, pitch and roll joints, the scaled arm has three actuators and 6 sensors. To be conservative, assume that four actuator commands are required, eight measurements are taken and the computer requires up to thirty-two internal states. The following numbers assume a 30% overhead for conversion and a 30% overhead for housekeeping by the computer. With these parameters, the required sampling rates for various controllers are

Output feedback: 69.5 kHz
General form (with estimator): 1450 Hz
Input canonical form: 11.6 kHz

Table A.2.1. Scaled properties of the RMS test article.

Quantity	Full Scale (λ=1)	Replica Scale (λ=1/8)	L/FFD Multiple Scale (λ_g=1/8, λ=1)	L/FFD Multiple Scale (λ_g=1/8, λ=0.4)
Total length (ft)	50	6.25	6.25	6.25
Tube diameter (in)	13.25	1.66	1.66	1.66
Wall thickness (in)	0.08	0.01	0.01	0.01
Bending modes #1 & #2 (Hz)	0.365	2.92	0.365	0.913
Bending modes #3 & #4 (Hz)	2.950	23.6	2.950	7.38
Bending modes #5 & #6 (Hz)	9.000	72.0	9.000	22.5
Mass per unit length	m	0.0156	8	0.512
Bending Stiffness ($lbin^2$)	1e9	244,000	1,950,000	780,000
Linear displacement	δ	0.125	1	0.4
Rotational displacement	θ	1	8	3.2
Time	t	.125	1	0.4
Moment	M	0.00195	0.125	0.02
Linear Velocity (ft/s)	2	2	2	2
Linear Acceleration	a	8	1	2.5
Angular Velocity (deg/s)	4.76	38.08	38.08	38.08
Angular Acceleration		64	8	20
Total mass (slugs)	28.89	0.056	28.89	1.85
Moment of inertia (slug ft^2)	600	0.018	9.36	0.6
Gravity deformation		.125	1	0.4
Buckling margin		1	8	3.2
Motor:				
Rotor/Gearbox Inertia. (slug ft^2)	0.00028	8.54e-9	4.38e-6	2.8e-7
Torque Constant (ft lb/Amp)	0.17			
Rate Loop Filter Time Const (sec)	0.10	0.0125	0.125	0.04

L/FFD: Length/Frequency-Force-Displacement, λ_g is geometric scale factor

These frequencies are well above the Nyquist frequencies necessary for the control and measurement of the fundamental modes of the arm. However, control algorithms for flexible robotic structures can be more complicated and require more computational operations per cycle than those generally associated with control of flexible structures. The above numbers do show us that there exists sufficient margin to handle this additional computational burden. On the real RMS, only 3 actuators and 6 sensors are available (not counting the wrist actuation and sensing, which will not be scaled)

A.3 TESTING PROCEDURE

The initial test should be a familiarization-coordination maneuvering test for the astronaut with the scaled test article in open loop. The test article would be attached to the middeck wall and the astronaut would manually re-orient the arm using a joystick or similar device. This should be followed by a repositioning slewing maneuver test, first in open-loop, and then followed by input shaping, active flexible control, and automated terminal lock-on tests. Tests could also be conducted with various payloads attached to the arm, including flexible and actively controlled structures. Also, the tests that were performed at the ground based RMS testing facility could be repeated with the same performance objectives but attempting to increase the measured performance.

Sensors on the arm can include joint position and velocity sensors, distributed flexible sensors (strain gages, accelerometers, etc.), external initial and terminal position sensors (Sel-Spot) and initial and terminal contact pads to demarcate the start and finish of the maneuver.

Acquired data should include the astronaut input profile, the shaped input profile, the manipulator tip trajectory (if obtainable), the various joint response time histories and maneuver start and finish times.

Once a payload whose mass exceeds some critical multiple of the manipulator arm is attached, the fundamental frequency of the manipulator is that associated with the arm acting primarily as a massless spring. The flexible modes associated with the distributed mass of the arm are much higher in frequency. Therefore, it is more in line with the MACE objectives to test payload configurations and maneuver profiles which are coupled with the manipulator distributed flexibility modes.

Possible follow-on test could include simulation of the orientation sequence that would need to be carried out in deployment of large payloads such as the Hubble Space Telescope of the Space Station modules. This would involve attaching the test article to a

free floating structure with inertial actuators allowing rigid body orientation and using it to orient another structure whose mass is approximately 1/4 the mass to which the scale model is attached. Another test could involve simulation of RMS assisted shuttle docking maneuvers.

A.4 EVOLUTIONARY OPTIONS

It is hoped that follow-on test articles can address some of the issues raised on Technology Development for Flexible Manipulators. In particular, incorporation of additional degrees of freedom, free-float testing, and additional links are options which may be pursued. Utilisation of the baseline RMS scaled hardware would help in containing costs for any follow-on experiment.

A.5 SUPPORTING TEST PROGRAMS

Several supporting test programs exist. FACE for Flexible Arm Control Experiment, with Dr. Eric Schmitz as principle investigator, is an OAST in-space definition study. The objectives of the program are several fold. The first objective is to validate dynamic models of the elastic manipulator under small angle motions, identify mode shapes and frequencies and characterize joint dynamics. A second objective is to validate nonlinear rigid/elastic dynamic models for large angle motions. A third objective is to demonstrate high bandwidth controllers. A fourth objective is to demonstrate compliant controller using end effector with a force/torque sensor to actively monitor interaction forces with environment and handle and minimially disturb large flexible payloads.

In support of the flight test program, Dr. Schmitz is developing a 2-D ground testbed with a full scale test article possessing 4 dofs, a 15 ft reach, a fundamental frequency of 1 Hz unloaded, a fundamental frequency of 0.2 Hz with maximum payload and a 2 ft/sec unloaded tip speed.

A second effort is being conducted by Draper to perform fast articulation experiments with the Shuttle RMS. The MACE program might supplement this program by performing scaled model testing of the RMS on the middeck as a method for extending and clearing the operational envelope of the RMS. This concept is discussed in detail in Section 2.3.5.

Contacts that have been initiated with experts in the areas of flexible manipulators and multi payload platforms. Experts in flexible manipulators include Prof. Warren Seering at MIT, Prof. Sandy Alexander at MIT, Prof. Cannon at Standford and Dr. Eric

Schmitz at Martin Marrietta. The MIT SERC plans to work closely with the NASA LaRC CSI Office on the multi payload platform test program. Finally, it is hoped to draw upon the resources available at the current ground based RMS test facility, both in algorithm development and comparison with previously conducted tests.

A.6 GROUND TEST PROGRAM

A study is presented in the next sections which investigates wether a scaled model of the RMS can be tested on earth without any support mechanism. The issues that are being addressed include braking torque, joint flexibility, gravity deflection, material failure, stall torque, and buckling. Depending on the results of this study, an unconstrained ground test will be carried out. Otherwise, alternative configurations to permit testing of the scale model test article are presented in the section in Technology Development for Flexible Manipulators.

A.7 GRAVITY EFFECTS ON THE SHUTTLE RMS

The purpose of this section is to determine the effects of a 1-g field on the shuttle Remote Manipulator System (RMS), with and without a 32000 lb tip mass. The question central to the analysis which follows is how small must the earthbound model be in a replica scale in order to avoid undesirable static structural response based upon several criteria. The criteria used include slippage at the joints due to insufficient stall or motor breaking torques, maximum desired deflections due to joint and member flexibility, and structural failure in transverse bending of the manipulator oriented horizontally. (Work in progress deals with buckling failure of the RMS in the vertical position.) As a point of interest the capabilities of the full scale RMS shoulder joint motor in the 1-g field is investigated by determining the angular deflections (from vertical) of the hanging system.

The model used in this evaluation is shown in Figs. A.7.1 and A.7.2. The actual RMS is divided into seven members connecting seven joints: swing out (1), shoulder yaw (2), shoulder pitch (3), elbow pitch (4), and wrist pitch, roll, and yaw (5-7). In this work only the pitch deflections were considered, so joint (3) is considered to be the root of the RMS system. In addition, the wrist assembly (members and joints 5-7) is assumed to be rigid. The RMS structural members are graphite/epoxy tubes of uniform cross section with 13.25 in. outer diameter (according to Reference [1]). Relevant data on the various members are presented in Table A.7.1, also from Reference [1]. The inner diameter of

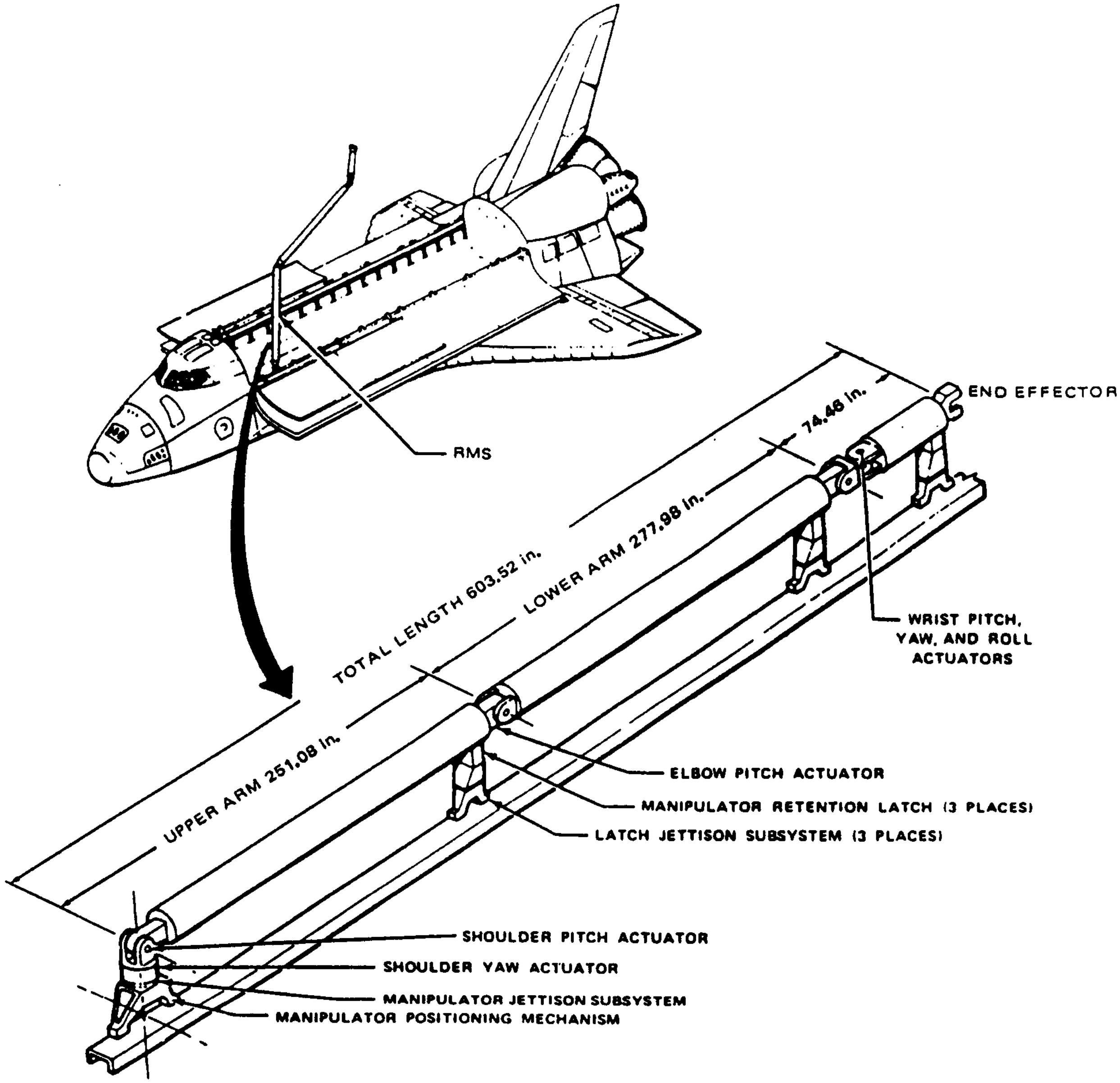


Figure A.7.1 **Manipulator flexible arm assembly showing location on the orbiter**

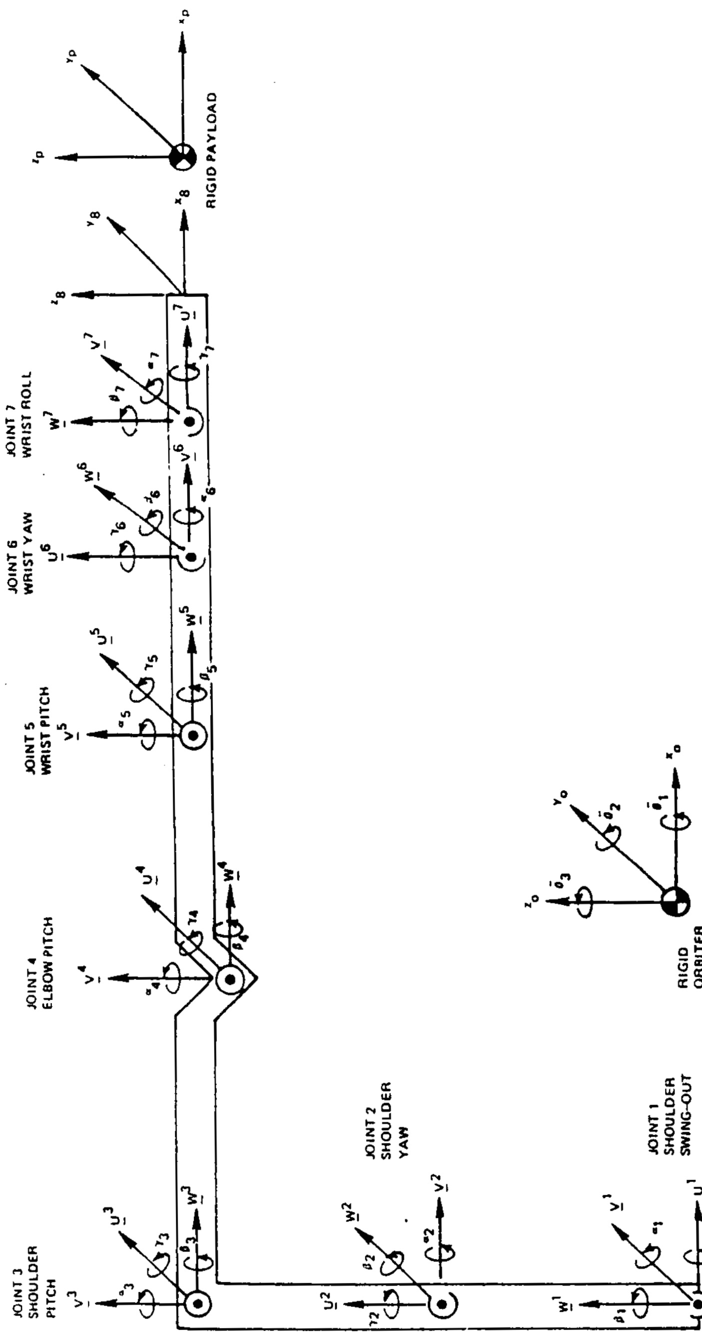


Figure A.7.2 **Schematic of remote manipulator arm in the stowed position depicting the joint axes and the degrees of freedom included in an ASAS-type simulation. The flexibility of each of the seven links is approximated by their first two vibrational modes.**

each member and the corresponding cross sectional moments of inertia are calculated by assuming a modulus of elasticity, E, of 20 x 10^6 psi and using the bending stiffness data from [1]. The two pitch joints (3 and 4) of importance here are considered to be massless with stiffnesses of 4.78 x 10^6 ft.-lb/rad (shoulder) and 2.32 x 10^6 ft.-lb/rad (elbow).

Table A.7.1 RMS Structural Parameters

Link	Length (ft)	Mass (slugs)	Stiffness (lb-ft2)	mass/length (slug/ft)	Tube Thickness (in)	Inertia (in4)
3	20.924	9.536	1.021 x 10^7	0.456	0.082	73.5
4	23.165	5.982	6.826 x 10^6	0.258	0.038	34.2
5	1.500	0.580				
6	2.496	3.144				
7	2.208	3.094				

A.7.1 Case 1: Motor Stall Torque

In this case the RMS is oriented horizontally and the effect of its weight at the shoulder pitch joint is considered. The motor at this joint, including the gear system, is capable of exerting up to approximately 1000 ft-lb of torque at zero angular velocity (this is the stall torque, τ_s), while the total moment due to gravity, M_g, is seen to be 19941 ft-lb. Thus the full scale RMS is incapable of supporting its own weight in a 1-g field. If the arm is replica scaled, with a scale factor of λ, Reference [2] indicates that applied torques scale with λ^3. The moment due to gravity scales as (mass)x(length), and [2] states that mass scales with λ^3, so the gravity moment scales with λ^4. For the two torques to be equal,

$$\lambda^3 \tau_s = \lambda^4 M_g \tag{1}$$

Using this equation it is found that the earthbound model with a scaled motor/gear system must be no larger than (λ =) 0.05 times the full scale RMS. If the 32000 lb tip mass is added, M_g = 1609300 ft-lb and the model, including a scaled tip mass, must have scale no greater than λ = 0.00062.

Clearly the shoulder joint motor/gears cannot support the arm horizontally. The question is how far from vertical can this system, when hanging, travel in a 1-g field. The angle is

$$\theta = \sin^{-1}\left(\frac{\tau_s}{M_g}\right) \tag{2}$$

Without the tip mass theta is 2.87°, while the tip mass reduces the angle to 0.0356°. The necessary scale factors derived above represent the point at which theta reaches 90° and the scaled motor is fully effective.

While these results indicate certain potential problems in earthbound modeling of the RMS, it is not clear that a scaled motor and gear system is neccesary for a useful dynamic test article. It is more important to consider the effects of joint and link flexibility under the 1-g field.

A.7.2 Case 2: Deflections Due to Flexibility

The RMS is once again oriented horizontally (theta = 90°), and the deflection due to gravity is calculated by superposing the result of a simple beam problem with rigid joints and cross sectional properties found in Table A.7.1 (where the wrist assembly merely causes a resultant force and moment at the end of link 4) and the result of the deflections purely due to joint flexibility with rigid links. In this work the bending moments due to gravity are considered constant (any effect due to foreshortening on the moment arms is neglected). The deflection at the tip of link 7 due to link flexibility of the full scale RMS without the 32000 lb end mass is found to be 1.44 ft, or 0.0286 times the total length (of links 3-7), which seems acceptible. The full scale tip deflection due to joint flexibility is easily seen to be 0.190 ft., which adds another 0.0038 times the length to the figure above, making the total deflection equal to (0.0324)x(length). When the 32000 lb end mass is added to the problem the total deflection under the constant moment assumption is given as several times the beam length of 50.3 ft, which is clearly impossible, indicating probable structural failure.

When the joint flexibility is ignored, the simple beam moment-curvature relation holds.

$$w'' = \frac{M_g}{EI} \tag{3}$$

Here w(x) is the beam transverse deflection and EI the bending stiffness, which is piecewise constant. Reference [2] indicates that in replica scaling EI follows λ^4, as does M_g, so the curvature is the same in the model as in the full scale. Integrating (3) twice to obtain w adds two factors of length, however, so the deflection scales as λ^2. (Alternatively, the nondimensional deflection w/l scales as λ.) If a maximum desired nondimensional tip deflection of 0.05 is desired in the model with a scaled end mass, it is seen that λ must be no greater than 0.017. (For a model of this size, the constant moment assumption is valid.)

A.7.3 Case 3: Link Failure

If the joint flexibilities are once again ignored and the arm treated as a piecewise uniform simple beam the stresses at the root can be calculated using

$$|\sigma_r| = \frac{M_g z}{I} \tag{4}$$

where z is the distance from the midplane of the tube. For the arm alone it has been indicated that M_g = 19941 ft-lb. Using this figure, the area moment of inertia of link 3 from Table A.7.1, and z = 6.625 in. (0.552 ft) the maximum stress is calculated to be 3.11 x 10^6 lb/ft^2. The strain at the surface of the tube at the root is then, under the assumption that E is 20x10^6 psi, equal to 0.00108. Graphite/epoxy failure occurs at strains of approximately 0.01, so in the full scale without the end mass there will be no link failure.

If the end mass is taken into account, however, the root surface strain

$$\varepsilon_r = \frac{M_g z}{EI} \tag{5}$$

is seen to be 0.087, far exceeding the failure point. Using the known scale factors presented previously, understanding that z scales with λ in the replica case, (5) shows that the surface strain scales with λ. So the earthbound model with a scaled end mass will not fail provided the replica scale factor is no larger than about 0.11. Of course the result from Case 2 indicates that the tip deflection at this scale will exceed the 5% desired limit.

A.7.4 Conclusions

In general, it has been shown that it will be difficult to build a useful earthbound replica scale model of the RMS due to the small scales required in order to avoid undesirable gravity effects. Most of the problems involve the joints, however, and the scaling issues involved were dealt with only generally. It was mentioned, for example, that it may not be necessary to use a scaled motor with the accompanied scale stall torque if a more powerful motor of similar weight can be found, or if the gear ratios may be adjusted.

Another issue to be addressed is the use of other types of scaling. Replica scaling does not, for example, preserve the natural frequencies of a structure. For an appropriately scaled dynamic model the issues discussed above will have different results.

A.7.5 References

[1] Abelow, Allen V., "Dynamic Equation Set for a Simplified Simulation of the Space Shuttle Remote Manipulator System," Charles Stark Draper Laboratory Report R-1258, 1980.

[2] Crawley, E. F., Sigler, J. L., and van Schoor, M. C., "Prediction and Measurement of Damping in Hybrid Scaled Space Structure Models," MIT Space Systems Lab Report 7-88, 1988.

Appendix B: Alternative Test Articles

B.1 PRECISION ALIGNMENT TEST ARTICLE

As mentioned in Section 2.1 regarding the potential roles of on-orbit flight experiments, a plausible role is the *demonstration* of capability to potential civilian and military users. Such a demonstration would be undertaken when it is felt that a particular technology has reached a level of maturity that it is ready for application. One purpose of the demonstration is to verify that issues associated with the on-orbit environment can be adequately dealt with in ground based experimentation and computer simulation. In other words, it is beneficial to demonstrate to potential users that there no longer exist any fundamental surprises associated with the technology that arise due to the transition from the ground to the on-orbit environment. A second purpose of the demonstration is to use the technology to achieve mission-typical requirements in the environment in which the mission would be carried out. Finally, a third purpose of the demonstration is to develop procedures for the debugging and fine tuning of a precision alignment test article on orbit

Due to the growth of extensive technology development programs for optical interferometry at MIT and JPL, the precision alignment test article was chosen to focus on optical interferometery. This coordinates the middeck flight test with existing ground test programs.

The ground test articles in these two programs are presently envisioned to be actively controlled truss structures of high enough stiffness to support their own weight and provide frequency separation between modest suspension schemes and the elastic modes. Therefore, it is a reasonable to assume that relevant ground test programs can be conducted. The dominant gravitational issue that needs to be addressed is how to accommodate the elimination of gravity deformations, which on the nanometer level result in significant deformations at any reasonable structural scale, as the test article transitions from ground based testing to on-orbit testing.

The second issue pertains to the demonstration of performance capabilities. In precision alignment, the objective is to demonstrate the level of precision control capable in light of on-orbit disturbances. Towards this end, the middeck environment can be used to minimize disturbances by free floating the test article in the evacuated airlock. This eliminates disturbances due to both acoustic excitation and transmission through the

suspension. The airlock provides protection for the astronauts from stray beams associated with any laser metrology system that might be used and eliminates measurement noise associated with variations in the refractive index of air. The middeck environment enables magnetic isolation schemes to be more easily implemented without need for a DC bias to off-load weight.

The last issue pertains to the development of procedures for the debugging, testing and fine tuning of precision systems on orbit. This could involve local (astronaut) or remote (up/down link) interaction. This process can be particularly difficult for laser metrology systems. The development of such procedures helps to refine the protocal for launching future precision alignment instruments and does so using less expensive hardware.

With these issues in mind, the next task involves selecting the test article configuration which addresses technology issues associated with interferometry.

B.1.1 Test Article Configuration

Proposed orbital optical interferometers generally consist of several optical elements passively held in relative orientation by a moderately rigid truss structure. The light impinging on the optical elements is recombined to generate an interference pattern whose central fringe yields magnitude data for a segment of sky subtended by the angular resolution of the interferometer, determined by the baseline of the instrument. For interference, light from the same wavefront must be recombined. This requires that the optical pathlengths be similar, on the order of a fraction of the wavelength (for optical wavelengths on the order of 0.55 μm, $\lambda/20 = 27.5$ nm). Vibrations in the truss degrade the performance of the interferometer. In ground based interferometers, this vibratory motion is reduced by controlling optics on active mounts which react against rigid and massivesupports. In an orbiting truss structure, the control of the active optics may potentially interact with the flexibility of the truss. Therefore, it may be appropriate to also control the elastic behavior of the supporting truss. This is the origin of the Controlled Structures Technology issue in orbital optical interferometry.

The objective to testing an on-orbit test article is to demonstrate technologies which meet or surpass the requirements of optical interferometry. All vibratory motions in the truss degrade performance but, as shown in Fig. B.1.1, the three most sensitive motions are shear in the line-of-sight (LOS) axis, relative rotation in the LOS plane and relative rotation out of the LOS plane.

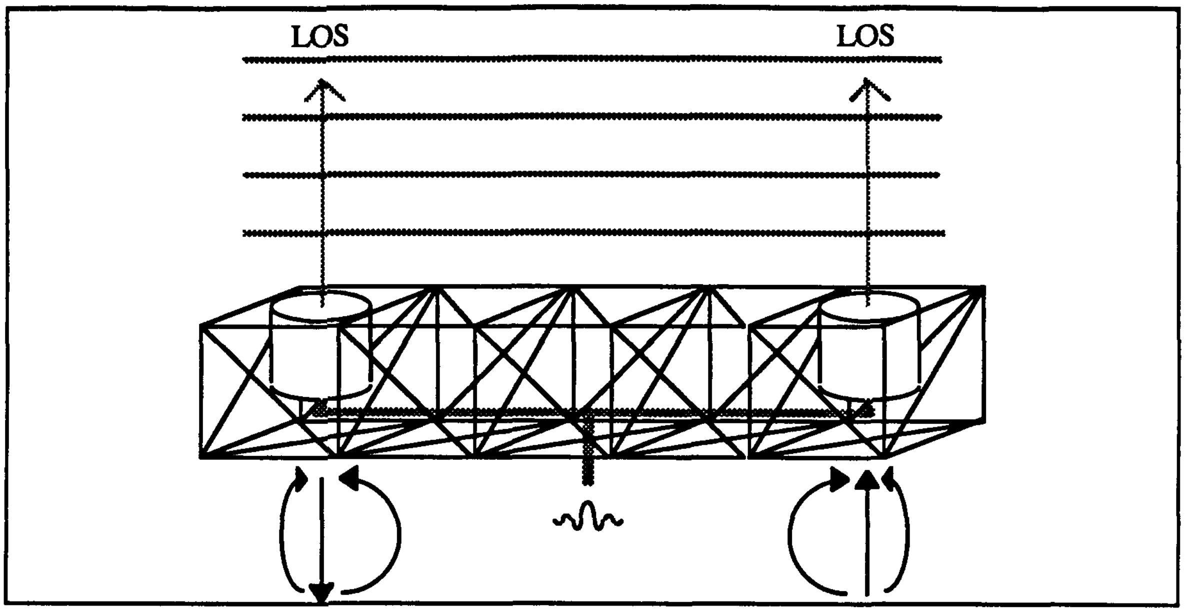


Figure B.1.1 **Generic orbital optical interferometer and sensitive vibratory motions**

The primary objective is to interfere light from two different spatial locations of the same wavefront. As opposed to radio interferometry, the optical interference must be performed in real time since the extremely high frequency of the phenomenon prohibits recording and interference through post processing. Therefore, the two optical pathlengths from wavefront to the interference location must be almost identical to within some fraction of the wavelength (*e.g.* $\lambda/20$). For optical wavelengths centered about 0.5 μm, $\lambda/20 = 25$ nm. Several factors effect these path lengths. First, if the line of sight is not perpendicular to the baseline, then the wavefront impinges upon one siderostat before the other. This can be remedied by either placing optical delays between the siderostats and the interference location, as is proposed in the JPL FMI design, or rotating the interferometer such that the LOS is perpendicular to the baseline, as is proposed for COSMIC. Second, the pathlengths can be distorted by bending or shear deformations in the structure. To avoid violating the $\lambda/20$ criteria, nonsymmetric bending or shear deformation amplitudes, in the plane defined by the LOS and baseline (meridional plane), at each siderostat must be held to less than 12.5 nm This can be remedied by either controlling the structure to this level, controlling the positions of the fold mirrors, by compensating for the motions by varying the optical delays or by a combination of all three techniques. Third, nonsymmetric axial motions must be maintained to less than 12.5 nm in amplitude at each siderostat. Axial motion also alters the baseline this blurring the interference pattern and degrading the angular resolution.

Another factor which degrades performance is relative rotation between the two siderostats. The requirement for relative angular rotation is directly proportional to the diameter of the siderostat which is inversely proportional to the field of view.(FOV). Larger diameter mirrors, having smaller fields of view, have more stringent requirements with respect to relative rotation in the meridional plane. Eq. B.1 gives the relationship between FOV for a circular mirror and mirror diameter.

$$FOV = 1.22\frac{\lambda}{D} \tag{B.1}$$

The largest diameter monolithic mirror that, at present, can endure launch loads and retain required surface accuracy is that of the Hubble Space Telescope at 2.5 m diameter. If these are used as the siderostats, the FOV equals 50 masec. Therefore, the absolute rotation of the instrument must be maintained on the order of 5 masec. Dynamic jitter, or relative rotation, must be maintained on the order of 1 masec. For mirror diameters on the order of 0.3 m in diameter, as used in the MARK III interferometer, the FOV is 0.4 asec yielding absolute and relative rotation requirements on the order of 40 masec and 10 masec, respectively. Torsion of the truss, which results in identical degradation of performance, needs to be maintained to the same levels.

Bending resulting in rotation of the siderostats about the LOS is only detrimental to the extent that the fold mirrors rotate to cause misalignment of the light in the interference plane. This misalignment is a function of the length of the baseline and the diameter of the light beam. To restrict misalignment of 1 cm diameter beams to one radius for a 30 m baseline, typical of an instrument residing in the Shuttle Cargo Bay, relative rotation about the LOS must be limited to 34 asec, much less stringent than the requirements for the other relative rotations.

A test article which is representative of the associated CST issues could consist of a multi bay truss structure as shown in Fig. B.1.2 with dimensions of 2 m in length (l) and 0.4 m length sides (b) for cubic bays. The CST objective could involve controlling up to six of the relative degrees of freedom between the two end faces to as precise a level as possible.

Measurement of the six relative degrees of freedom, and therefore the performance, could be achieved using a six axis laser interferometer metrology system where each axis measures axial motion between an interferometer and a target mirror. Figure B.1.3 illustrates a candidate metrology geometry. Two interferometers are placed near each of three of four nodes at the left end of the truss. An equal number of target mirrors are

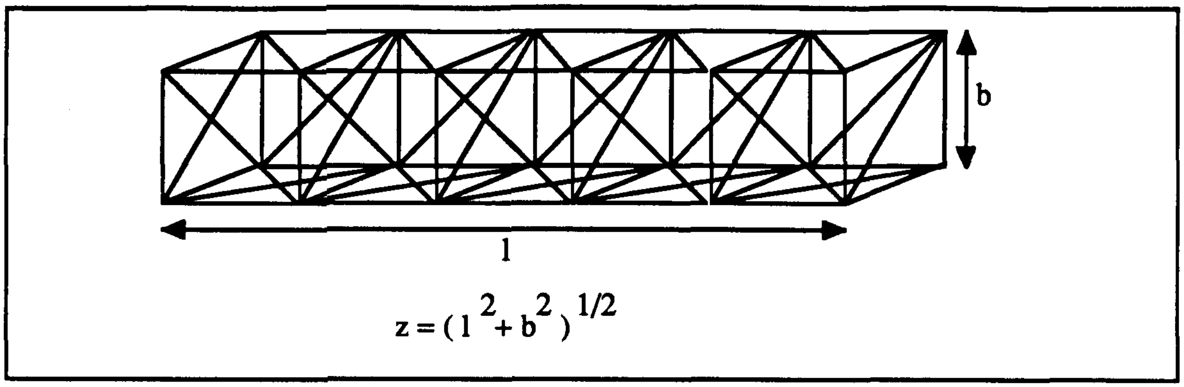


Figure B.1.2 **Multi bay truss representative of an orbital optical interferometer support structure.**

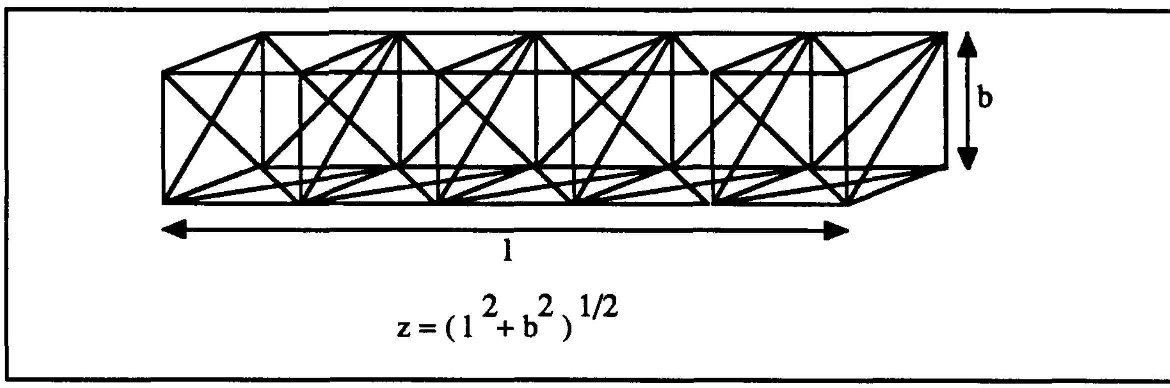


Figure B.1.2 **Multi bay truss representative of an orbital optical interferometer support structure.**

placed at nodes of the right end. The laser beams labeled z1 through z6 in Fig. B.1.3 measure three lengthwise axial motions and three side diagonalwise axial motions.

The axes defined in the bottom of Fig. B.1.3 correspond to the six relative degrees of freedom between the two end faces. Equation B.2 gives the transformation from the laser metrology measurements to the relative degrees of freedom as defined in Fig. B.1.3 . For a laser interferometer resolution of 1.25 nm, a truss length of 2 m and a truss width and heighth of 0.4 m, the relative motion resolutions are x1 = 1.25 nm, x2 = 12.5 nm, x3 = 12.5 nm, Θ1 = 5 masec, Θ2 = 1 masec and Θ3 = 1 masec. As seen in Table B.1.1, these resolutions for existing interferometric metrology technology are on the

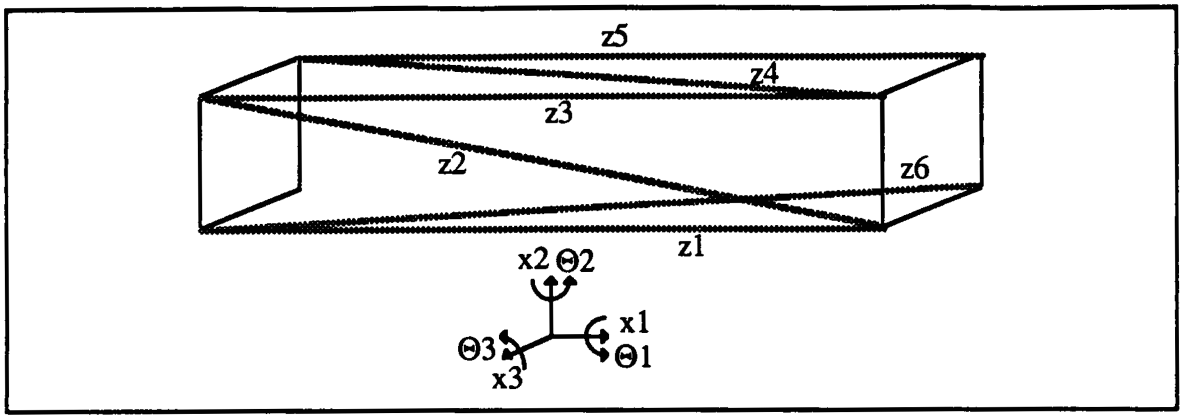


Figure B.1.3 Laser metrology measurement paths.

Table B.1.1 Comparison of optical interferometry requirements and laser metrology capabilities

Relative motion	Requirement	Capability
Θ1	1 - 10 masec	5 masec
Θ2	34 asec	1 masec
Θ3	1 - 10 masec	1 masec
x1	12.5 nm	1.25 nm
x2	12.5 nm	12.5 nm
x3	?	12.5 nm

order of that required by the optical interferometer mission described above.

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ \theta_1 \\ \theta_2 \\ \theta_3 \end{bmatrix} = \begin{bmatrix} \frac{1}{2} & 0 & 0 & 0 & \frac{1}{2} & 0 \\ \frac{l}{2b} & \frac{-z}{b} & 0 & \frac{z}{2b} & \frac{-l}{2b} & \frac{z}{2b} \\ \frac{l}{2b} & 0 & \frac{-l}{b} & \frac{z}{2b} & \frac{l}{2b} & \frac{-z}{2b} \\ \frac{-l}{b^2} & 0 & 0 & \frac{z}{b^2} & \frac{-l}{b^2} & \frac{z}{b^2} \\ 0 & 0 & \frac{1}{b} & 0 & \frac{-1}{b} & 0 \\ \frac{1}{b} & 0 & \frac{-1}{b} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \\ z_5 \\ z_6 \end{bmatrix} \tag{B.2}$$

In addition to a six axis laser metrology system, other sensors may be required. Typically these other sensors would be strain gauges, micro gravity accelerometers and any dual sensors associated with the actuators. The actuators must be load carrying actuators since nonload carrying actuators, such as proof mass actuators, would tend to exhibit significant stiction at these nanometer levels. There must be at least an equal number of actuators as axes being controlled to ensure independent axis control. These actuators could include piezo electric members and piezo or magnetic optics mounts. Active/passive actuators could include worm gears, inch worms or telescoping mechanisms. Measuring

absolute distance would require a laser ranging device which is presently limited to millimeter accuracy.

The structure would consist of a five bay truss 2 meters in length with cubic bays 0.4 meters on a side.

Scaling the precision requirements as the geometric scale (~15) would result in requirements tighter than the resolution of available laser metrology systems. However, since this experiment is for technology demonstration, scaling is not as important as absolute demonstrated performance.

B.1.2 Testing Procedure

There exist two aspects to the precision alignment problem. The first consists of minimization of the vibratory behavior about the passive alignment of the structure. The second consists of controlling both the vibratory motion about the static alignment and the static alignment about some desired alignment.

The first step in developing the test plan consists of devising a way to capture the laser metrology system. This can consist of manual adjustment, which would probably not be representative of the manner in which the metrology system would be aligned for an operational orbital interferometer, or automatic scanning and lock-on can be used.

The second step consists of picking the axes to be controlled (1 through 6). These axes can correspond to some subset of the sensitive axes for optical interferometry (Fig. B.1.1).

The third step involves designing the structure passively to minimize these motions through structural mistuning, broadband damping, or tuned damping elements.

The fourth step consists of actively minimizing the vibratory motion along the chosen axes.

The fifth step consists of performing additional active control of the alignment using active and active/passive actuators. This step not only involves the minimization of the dynamic misalignment but also the quasi static drift from some desired shape. The latter introduces the need for active/passive actuators which can be actively controlled, at low bandwidth, but support residual loads passively. This step also raises the issue of capture of initial shape or the adjusting of the structure to a desired alignment after assembly or deployment of the test article.

For present ground-based interferometry, the compensation for pathlength is performed through active optic mounts. One of the objectives of the precision truss test program should be to determine if or when this approach is sufficient to meet mission requirements. Therefore, perhaps several tests should be conducted where the optical metrology paths are controlled only using active optics mounts for comparison of performance.

Several options exist for testing the precision truss. In the first option, the truss can be tested in vacuum in the airlock. However, as was discussed in Chapter 3, a suited astronaut is required in the airlock in order to depressurize it. This not only limits the amount of volume available for the test article, it greatly increases the safety concerns. Therefore, as presently configured, testing in vacuum in the airlock does not provide significant advantages over testing in the cargo bay.

The second option involves testing the precision truss in the middeck. This can create a potential safety hazard to the crew due to the numerous laser beams involved in the laser metrology system. This might be remedied by using the hollow members to contain the laser beams.

A third option involves testing the precision truss in air in the airlock. In this option, the crew is protected from stray laser beams due to the containment vessel of the airlock and the test article is isolated from air currents and acoustic excitation that would exist in the middeck. This option seems most promising and will be expanded upon further in the following discussion.

Once in the airlock, the test article can be cantelevered off the containment vessel, suspended by a very soft suspension, or free floated. Each configuration provides an element of dynamic isolation surpassing that of the previous. This reduces the burden on the control to reduce large disturbances and allows it to focus on controlling the micro dynamic response.

The laser metrology system measures two quantities. The first is the relative axial motion between the interferometer and the target mirror. The second is the refractive index of the air through which the laser beam travels. Testing in vacuum would eliminate measurement noise associated with the latter. However, as stated previously, this option is not presently available. Therefore, the control objective should be to minimize the six relative end face motions as measured by the metrology system.

Two limiting scenarios exist. In the first, if there are no fluctuations in the refractive index of air, then the control minimizes the relative motion as desired. In the

second, if there is no relative motion but the refactive index of air is fluctuating, then the control objective is to dynamically deform the truss in order to minimize the measurement of the refractive index. Therefore, minimizing not only the relative motion of the end faces but also the measurement of the refractive index of air would demonstrate that if the air were not present, the performance would be consistent with the original control objective.

In the event that the precision truss test article is deemed too complex for a near term flight test, an enclosed cylinder, evacuated or filled with an inert gas, can be used for precisely controlling the relative axial motion between the two end faces. The enclosure provides safety from the laser metrology system and reduction of fluctuations in the refractive index of air. In addition, this test article could be tested in the middeck.

B.1.3 Supporting test programs

Two programs under NASA CSI funding have been initiated with interferometry as a focus mission. The Jet Propulsion Laboratories, with Dr. W. E. Layman as Task Manager, has formulated a program composed of various aspects of interferometer design. These aspects include Systems and Concepts, Analysis and Design, Testbed, Flight Experiments and a Guest Investigator Program. Supporting this effort are a Management Review Team and Technical Advisors (Dr. M. Shao, Dr. F. Tolivar and Dr. B. Wada). The Massachusetts Institute of Technology Space Engineering Research Center has a program with the following aspects: Systems and Concepts, Structures for Control, Control for Structures, Hardware/Test/Validation, Testbed, Flight Experiments (MODE & MACE) and a Visiting Scholar or Engineer Program. MIT SERC is supported by a Steering Committee composed of government, university and industry representatives and a Science Advisory Committee whose members which work on interferometry include Prof. Bernard Burke (MIT), Prof. David Staelin (MIT), Prof. Wes Traub (SAO) and Prof. Mike Shao (SAO).

Both programs would provide the supporting research necessary to complement a flight test of a precision alignment test article. To this end, JPL has offered to support MIT SERC in the precision alignment test program by providing input to the test article design, control and testing instrumentation, system ID and control algorithms and test protocal.

B.2 TECHNOLOGY DEVELOPMENT FOR FLEXIBLE MANIPULATORS

Multi payload platforms and articulated manipulators are distinguished based primarily on angular and linear articulation. Multi payload platforms contain instruments

which articulate through large angles. Articulated manipulators possess several links which maneuver through large angles with respect to the other links resulting in linear translation of the tip. Such systems require zero gravity technology *development* to accomodate the increase in the number of motion coupling mechanisms which arise when going from 2-D to 3-D. In addition, there is a need to eliminate the detrimental gravity deformations associated with point suspensions in the 1-g environment. Other reasons to test these CST configurations include the need to allow unconstrained motion of modes with nonplanar mode shapes, to avoid the constraint that 1-g suspensions often limit motion to small angles and displacements, to account for the possibility that while active suspensions may accomodate large motions, they may detrimentally or unrealistically interact with structure.

The development of a middeck testbed in these two areas enables the community to develop procedures for the debugging, testing and fine tuning of flexible, articulated systems on orbit. This could involve local or remote interaction. Since the middeck provides a limited volume to work in, the test article helps the community to address multibody and structural scaling issues. Middeck dynamic testing of the open and closed-loop systems enables verification of simulation tools and comparison of codes. In addition, ground testing does not determine actual space behavior since gravity effects may mask motion and increase damping, and suspension off-loading support may add or interact with structural dynamics

Difficulties associated with the control design include the coupled nonlinear dynamics and distributed flexibility and inertia. These couplings become much more numerous in three dimensions.

Ground testing can be more feasible using scaled test articles which have smaller nondimensional gravity deformation (deformation/length) allowing more realistic testing in 1-g but possibly add complexity and cost in manufacturing. The feasibility of scale model testing depends on the scale which is a function of buckling, drive stall torques, plasticity, etc.

B.2.1 Test Article Configuration

A flexible, articulated test article, representative of the issues needing development, would consist of multiple links with point and distributed flexibility which can be articulated in three dimensions with various known payloads attached. This test article can be mounted in two ways: in the initial configuration, it can be cantilevered off the middeck locker face or some other middeck attachment. Subsequently on future flights it can be

attached to a free floating base which can consist of a reaction mass or the multibody test article.

The base test article will consist of a two link flexible manipulator with two to three (2-3) shoulder degrees of freedom (pitch, yaw and maybe roll) and one ptich degree of freedom at the elbow. The wrist degrees of freedom are not included because the issues associated with the wrist are not CST issues. This base test article might be a second-generation concept design that evolves from the STS RMS, and might actually have some commonality in hardware with the scaled RMS test article that is proposed in a subsequent section. Initially, the test article would be cantilevered off the middeck locker face or some other middeck attachment.

Figure B.2.1 illustrates the dimensions and features of the base test article. The actuators consist of a pitch, yaw and roll actuator at the shoulder. These actuators can be belt drives, gear motors, stepper motors or direct drive motors. The elbow has a pitch actuator. Colocated sensors associated with each actuator could include potentiometers, tachometers, optical position and rate encoders, torque transducers, etc. Sensors and actuators could also be located between pivot locations internal to the links. These would be used for vibration isolation and suppression.

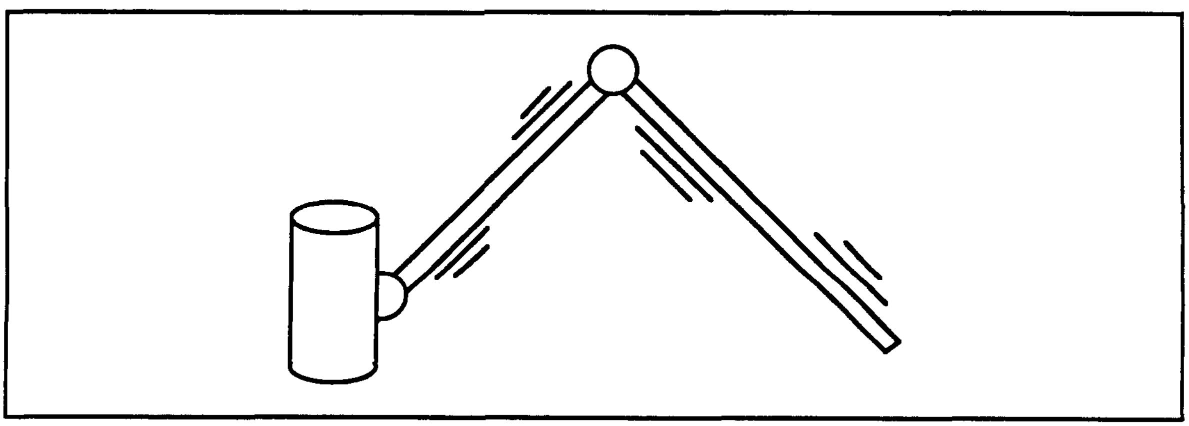


Figure B.2.1 Base test article.

External sensors may be required to sense the motion of the manipulator tip. 'Sel-spot', a lateral effect photo diode sensor, could measure the x-y position of a bright light located at the tip of the manipulator. A second 'Sel-spot' could be used to provide x-z plane coverage to extend sensor resolution to three dimensions. Such a noncontact, remote sensor capability could be used at the initial and terminal positions with the intermediate profile inferred from the drive sensors.

Subsequent flights of the test article might involve mounting it on a free floating reaction base or on one of the interface bays on the multibody platform. With an ambient gravity level of 2 x 10^6 g on the middeck due to drag and gravity gradient, it would take three minutes to drift one foot, four minutes to drift two feet and five minutes to drift three feet. Residual velocity associated with positioning of the test article reduces these drift times and could conceivably be the dominant effect determining free float times. Several other issues might also be addressed such as the addition of a third flexible link, the accommodation of unknown payload masses and the accommodation of the manipulation of active payloads whose dynamics become coupled to those of the manipulator.

B.2.2 Testing Procedure

Testing of the base test article would involve minimizing the maneuver time associated with articulation of the tip from one point to another in three dimensions. The articulation can be crew assisted or autonomous. When crew assisted, a crew member would have control over inputing a reference profile, computer profile shaping could be used to minimize excitation of flexible motion and feedback would be used to track the reference profile, damp flexible motion and provide minimization of terminal orientation error. In the autonomous mode, the system would be provided with the terminal coordinates and shaped feedback and feedforward inputs would be used to follow an appropriate profile.

The test objective for the base test article would be to reorient the tip in minimum time under a motion constraint. The constraint placed on the motion of the manipulator prohibits articulation rates which, if maximum braking from the drives were required or mechanical stops were impacted, would result in structural failure of the manipulator.

Figure B.2.2 illustrates the maneuver profile associated with a generic reorientation test. The test begins with the manipulator tip being held in precise orientation with respect to an external sensor. The controlling computer is then given the new coordinates and the maneuver concludes when the tip has achieved less than a threshold error in orientation with respect to a sensor located at these new coordinates. A noncontact, remote sensor capability could be used at the initial and terminal positions with the intermediate profile inferred from the drive sensors. Feedback could be employed at the initial position to maintain a degree of orientation with the first external sensor, at the terminal position to achieve a degree of orientation with the second external sensor, to suppress vibrations during the maneuver and to track the reference profile.

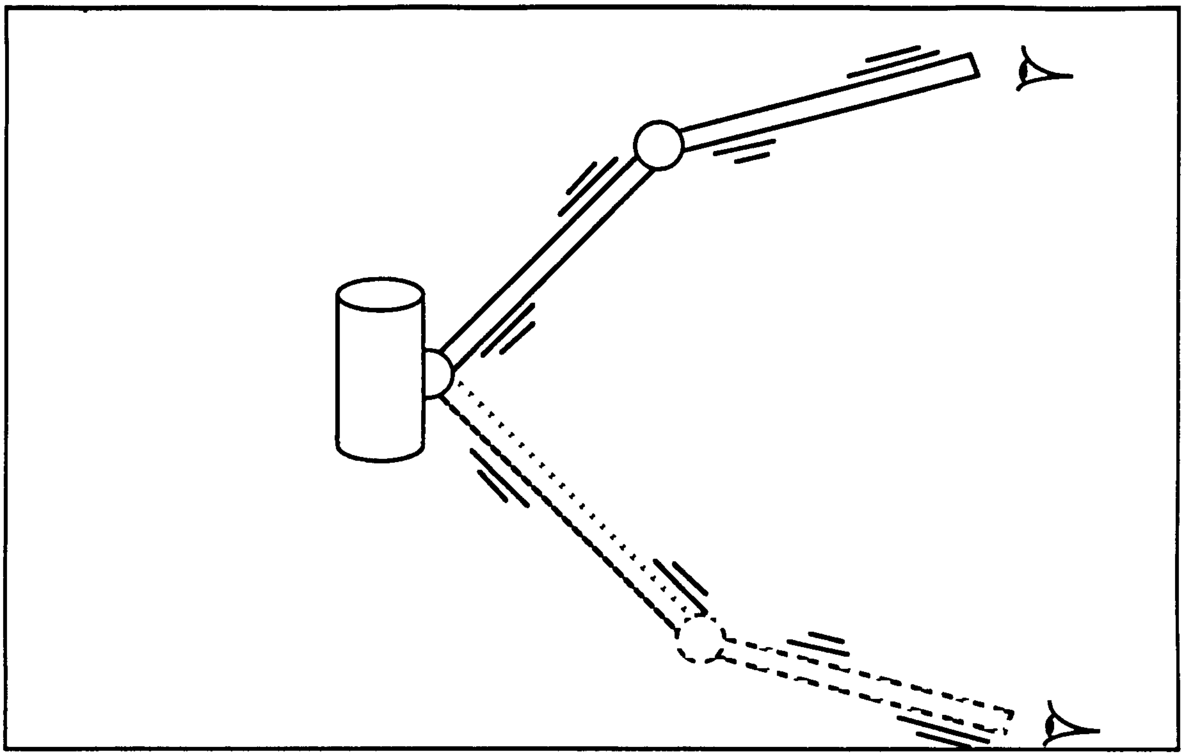


Figure B.2.2 Base test article motion profile.

In order to prevent collisions with other experiments on the middeck, a maximum operational volume would be pre-determined for both the crew-assisted and autnomous tests. The control computers in conjunction with mechanical stops would prevent motion outside this volume.

Issues that can be addressed in the tests are minimum excitation input profiles through torque shaping, on-orbit fluid modelling and interaction, pointing accuracy, jitter suppression, settling times, disturbance modelling, deployment dynamics and control, validation of system-level control approaches, vibration isolation, system ID, nonlinear verification of large motion and flexible models.

B.2.3 Supporting Test Programs

Several supporting test programs exist. FACE for Flexible Arm Control Experiment, with Dr. Eric Schmitz as principle investigator, is an OAST in-space definition study. The objectives of the program are several fold. The first objective is to validate dynamic models of the elastic manipulator under small angle motions, identifymode shapes and frequencies and characterize joint dynamics. A second objective is to validate nonlinear rigid/elastic dynamic models for large angle motions. A third objective is to demonstrate high bandwidth controllers. A fourth objective is to demonstrate compliant controller using

end effector with a force/torque sensor to actively monitor interaction forces with environment and handle and minimially disturb large flexible payloads.

In support of the flight test program, Dr. Schmitz is developing a 2-D ground testbed with a full scale test article possessing 4 dofs, a 15 ft reach, a fundamental frequency of 1 Hz unloaded, a fundamental frequency of 0.2 Hz with maximum payload and a 2 ft/sec unloaded tip speed.

A second effort is being conducted by Draper to perform fast articulation experiments with the Shuttle RMS. The MACE program might supplement this program by performing scaled model testing of the RMS on the middeck as a method for extending and clearing the operational envelope of the RMS. This concept is discussed in detail in Section 2.3.5.

Contacts that have been initiated with experts in the areas of flexible manipulators and multi payload platforms. Experts in flexible manipulators include Prof. Warren Seering at MIT, Prof. Sandy Alexander at MIT, Prof. Cannon at Standford and Dr. Eric Schmitz at Martin Marrietta. The MIT SERC plans to work closely with the NASA LaRC CSI Office on the multi payload platform test program.

The MIT SERC is defining, as its second in-house testbed, a multibody articulation and control testbed. Fig. B.2.3 illustrates three conceptual test articles that are being developed at MIT facilities or will be part of the SERC testbed.

B.3 FLIGHT QUALIFICATION USING SCALE MODELS

As mentioned in Section 2.1 regarding the potential roles of on-orbit flight experiments, a plausible role is the *qualification* of near term vehicles. Prior to this, however, is the need to develop flight *qualification* procedures. In addition, there is a need to develop methods for the debugging, testing and fine tuning of actual, full scale mission hardware on orbit. This could involve local interaction with suited astronauts or astronauts located in the Shuttle or could involve remote interaction with personnell on the ground.

The testing of scaled models on the middeck might provide a more cost effective means for identifying potential mission problems and solutions prior to mission launch. In addition, it could help map out or test beyond the flight hardware performance envelope without risking damage to actual, full scale flight hardware.

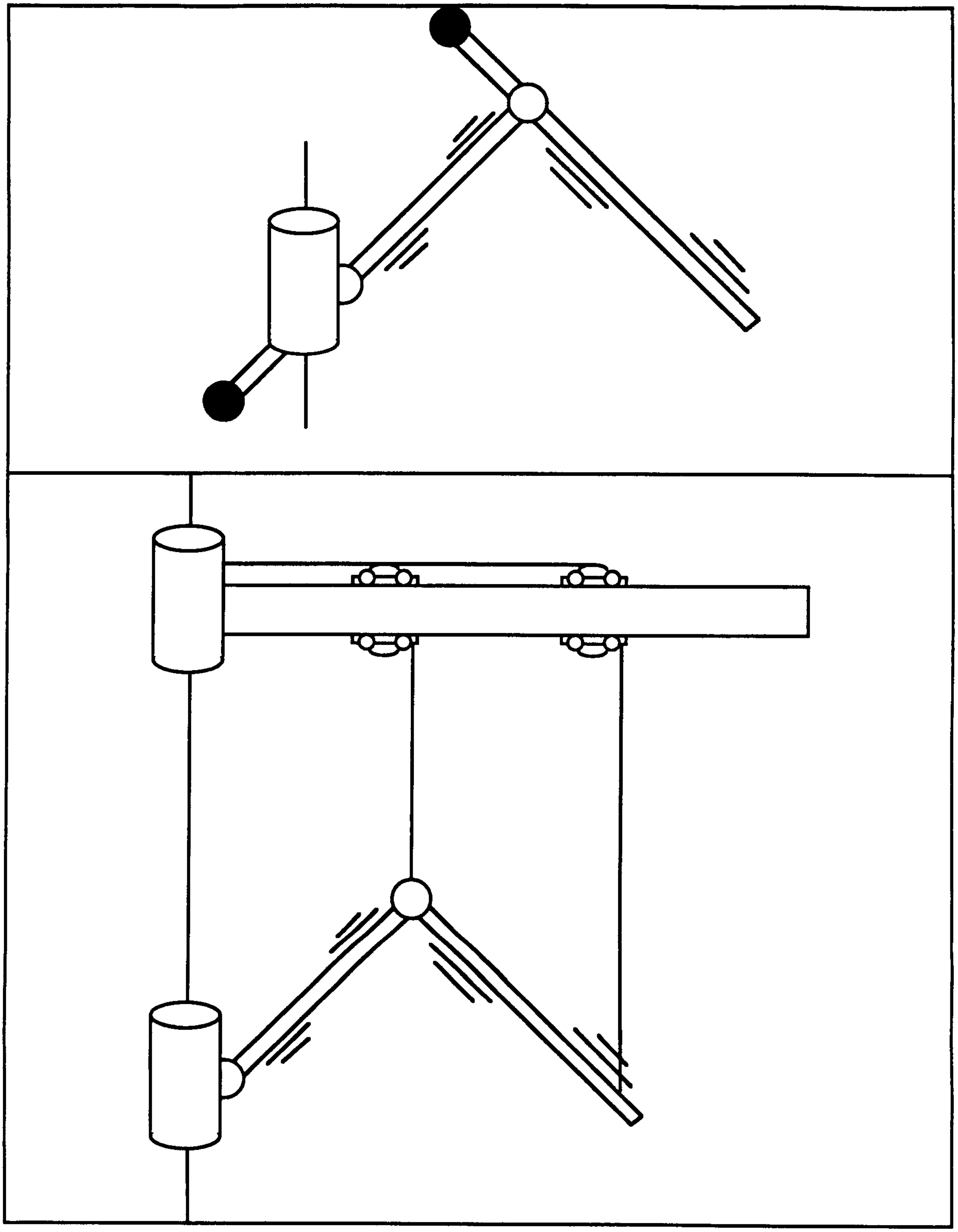


Figure B.2.3 Testbed and test article supporting facilities at MIT

B.3.1 Test Article Configuration

The most important aspect of developing procedures for or performing actual qualification is the availability of the on-orbit testing of the full scale companion instrument. This test provides the yardstick by which the value of the scale model testing is judged.

In this proposal, two instruments are proposed to be the focus of scale model testing. The first is a scale replica of the STS RMS and was discussed in Appendix A. The second is a scale replica of the STS RMS and was discussed in Appendix A. The second involves the testing of a scale model of the Controls, Astrophysics and Structures Experiment in Space (CASES) instrument. The selection of CASES is based upon its potential of being a relatively near term CSI flight test article. Actual mission selection should only be defined at the latest possible date to increase the assurance that the companion full scale test article will actually fly. Table B.3.1 lists the full and sub-scale parameters for CASES. Table B.3.2 lists the corresponding performance requirements.

Table B.3.1 Comparison of full and subscale parameters for replica scaling. Scale factor λ = 1/15

Parameter	Full Scale	Sub Scale
Total weight	13,600 lbs	4 lbs
Total power	3236 W	14.4 W
Boom length	105 ft	7 ft
TIP MASS ASSEMBLY		
Boom tip assembly structure	100 lbs	0.5 oz
AMEDS (3) & rate gyros (2)	15 lbs	0.07 oz
Thrusters	7 lbs	0.03 oz
Data acquisition control interface	2 lbs	0.01 oz
Roll torque motor	10.5 lbs	0.05 oz
Mass inertia imbalance device	70 lbs	0.33 oz
Boom tip power supply	5 lbs	0.02 oz
Contingency	20.9 lbs	0.1 oz
LOWER BOOM ASSEMBLY		
AMEDS (2) & rate gyros (2)	15 lbs	0.07 oz
Data acquisition control interface	2 lbs	0.01 oz
Lower boom power supply	2 lbs	0.01 oz
Structure	23 lbs	0.11 oz
Contingency	4 lbs	0.02 oz
TIP ASSEMBLY		
Weight	171 lbs	0.81 oz
I_x	11.81 slug ft^2	1.6EE-5
I_y	18.56 slug ft^2	2.4EE-5
I_z	24.74 slug ft^2	3.3EE-5
BOOM		
Weight	41.6 lbs	0.2 oz
EI	18 x 10^6 in lb	356 in lb
GJ	360,000 in lb	7 in lb
LOWER BOOM ASSEMBLY		
Weight	21 lbs	0.1 oz
I_x	48.97 slug ft^2	6.4EE-5
I_y	48.97 slug ft^2	6.4EE-5
I_z	97.18 slug ft^2	12.8EE-5
Interface stiffness	300,000 in lb/rad	5.9 in lb/rad
MODAL FREQUENCY (Hz)		
1 pure bending	0.03453	0.51795
2 pure bending	0.03475	0.52125
3 torsion	0.13058	1.95870
4 bending	0.50758	7.61370
5 bending	0.51277	7.69155
6 bending	1.50176	22.5264
7 bending	1.56234	23.4351

Table B.3.2 Comparison of full and subscale requirements for replica scaling. Scale factor λ= 1/15

Requirement	Full Scale	Sub Scale
Platform stability	3 asec	3 asec
Pointing	1 amin	1 amin
Relative tip/base displacement	1.5 mm	0.1 mm
Operation time	30 min	2 min
Jitter	4 asec/sec	60 asec/sec

Appendix C:
Detailed System Architectures

C.1 STD BUS ARCHITECTURE

C.1.1 Description

The STD bus architecture is illustrated in Figure C.1.1. The major feature of this option is the use of multiple microprocessors to implement the system architecture. Separate processors are dedicated to each of the following functions:

- System control and communications
- Signal generation
- Data acquisition
- Data storage
- Dynamics calculations

This configuration provides greater performance and easier software development, due to the following:

- Each processor has only one function to perform
- High rate functions are separated from low rate
- Bus use is minimized

The Master processor is responsible for experiment setup and real time interprocessor communications. Setup is performed prior to the start of the experiment; thus, during the execution of the actual experiment, the Master only performs its communications function. Experiment setup consists of the following steps:

- Download excitation parameters to Signal Generation Slave (SGS)
- Configure Analog Function Card as required
- Configure A/D Slave for data acquisition as required
- Configure Data Storage Slave as required to receive acquired analog data
- Configure DSP Coprocessor with the appropriate control algorithm
- Initiate the experiment execution

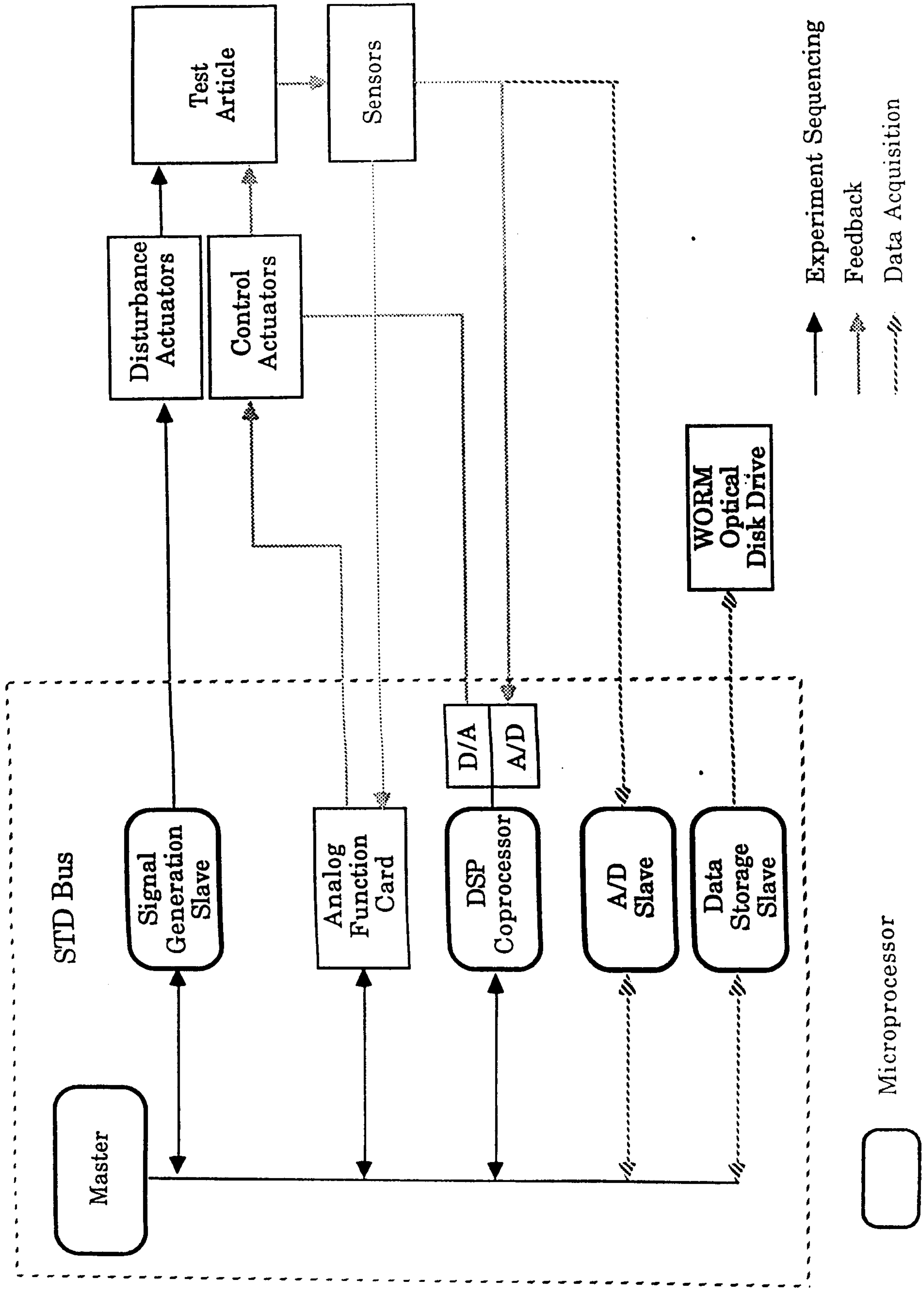


Figure C.1.1 STD Architecture

The Signal Generation Slave (SGS) is the excitation source for the power amplifier and shaker assembly. It consists of two elements: a waveform synthesizer and a microprocessor. The synthesizer is able to create waveforms with precisely controlled attributes (eg. frequency, amplitude, phase, etc.). The microprocessor controls the synthesizer, and is able to dynamically alter the resultant waveform as per requirements. For example, the Master could command the SGS to create a sweep of frequencies; the microprocessor would update the frequency selection to the synthesizer at the requested intervals, independently of the Master.

The DSP Coprocessor, along with its associated A/D and D/A modules, implements the digital control function. It acquires sensor data via its A/D module, performs the necessary dynamics calculations, and outputs the results through the D/A module. Different parameters, or even entire equations, may be downloaded from the Master prior to operation.

The data acquisition function is accomplished by the A/D Slave (ADS), and data storage is performed by the Data Storage Slave (DSS). Together, these two acquire the data that is later analyzed to determine the experiment results. The ADS samples a number of channels at the rate requested by the Master, assembles the data into packets containing several samples from each channel, and sends the resultant packets to the DSS for storage. The DSS is responsible for all buffering of data packets, optical disk drive control, and data formatting.

C.1.2 Performance Analysis

In any system architecture, data paths must be examined to ensure sufficient throughput to support their required throughput. Different line styles were used in Figure C.1.1 to depict the three functional types of data paths required of the MACE architecture: experiment sequencing, feedback, and data acquisition. Each of these data paths are examined in the following paragraphs.

Experiment Sequencing

The experiment sequencing data path is used to setup the various subsystems for any particular run. This is done before and after real time operations; therefore, the bus bandwidth is clearly adequate. This path also includes the input to the power amplifier and actuators, which is purely an analog signal produced by the SGS. Therefore, as long as the SGS is capable of generating the required analog signals, this data path is adequate.

Feedback Control

There are actually two feedback control loops. The first is an analog loop through the Analog Function Card. The other is the loop that is used in the digital control calculations. In this option, this loop passes only through the DSP Coprocessor and its dedicated A/D and D/A modules; therefore, the STD bus is unaffected by this data.

Data Acquisition

Data acquisition represents the only tasks requiring real time data transfers over the STD bus; therefore, it can be given nearly all of the STD bus bandwidth. The maximum data transfer rate between two boards on the STD bus at 8 MHz is one megabyte per second.

C.1.3 Implementation

Hardware

The three slave processors may be realized by using the ZT8832 intelligent control processor card produced by Ziatech Corporation, of San Luis Obispo, CA, who is a leading manufacturer of STD bus cards. There are a wide variety of A/D converter cards that may be used for the A/D Slave; one example is the CDX-AD816 iSBX A/D Converter produced by Computer Dynamics, of Greer, SC. There are several SCSI adaptors which may be used by the DSS; an example is the ZBX-288 SCSI Host Adapter manufactured by Zendex Corporation of Dublin, CA.

The DSP Coprocessor and its A/D and D/A Modules must be developed to meet the needs of the MACE architecture. The DSP chip recommended is the Texas Instruments TMS320C30 Third Generation Digital Signal Processor; this chip boasts an impressive list of features, some of the most pertinent of which are listed below:

- Third generation of widely-used DSP family
- Ample development tools (C compiler, assembler, simulator, emulator)
- 40/32-bit floating-point/integer multiplier and ALU
- 60 nanosecond single-cycle instruction execution time
- 33.3 MFLOP floating point performance
- 4K x 32-bit single-cycle dual-access on-chip ROM
- 2K x 32-bit single-cycle dual-access on-chip RAM

- On-chip Direct Memory Access (DMS) controller
- Two on-chip serial ports
- Two on-chip 32-bit timers
- 4 external interrupt inputs
- Low power (1.5 Watts) CMOS technology

Software

Software development is easily performed on IBM PC-AT class machines. A list of software tools required, as well as estimated costs, follows.

GENERAL TOOLS

- Text editor (Brief by Solution Systems) List $200
- Software version control (PVCS by Polytron) List $395

MASTER AND SLAVE PROCESSOR TOOLS

- Compiler (C 5.1 by Microsoft) List $450
- Assembler (MASM 5.1 by Microsoft) List $150
- Debugger (DBug-88, PC-STD,and LOCATE by Ziatech) List $650

DSP DEVELOPMENT TOOLS

- Compiler (TMS320C30 Optimizing C Compiler by Texas Instruments) List $2500
- Assembler (TMS320C30 Macro Assembler/Linker by Texas Instruments) Included in the TMS320C30 Optimizing C Compiler package or List $500
- Simulator (TMS320C30 Simulator by Texas Instruments) List $1500
- Emulator (TMS320C30 Emulator (XDS1000) by Texas Instruments) List $10,000

C.2 PC-AT BUS ARCHITECTURE

C.2.1 Description

The PC-AT bus architecture is illustrated in Figure C.2.1 Note the similarity between this configuration and that of Figure C.1.1. Each block in the STD bus option is

also present in the PC-AT bus option. The only significant difference between the two is the greater number of microprocessors utilized by the STD bus system.

C.2.2 Performance

Analysis of the PC/AT architecture shows that performance will be very similar to that achieved for the STD bus, for each of the signal/data paths. The hardware implementation discussion below describes how the specific requirements may be met with currently available technology.

C.2.3 Implementation

Hardware

There are several A/D cards that will meet the requirements for data acquisition; an example is the DT2821 Analog I/O card by Data Translation of Marlboro, MA. This card also provides 16 digital I/O lines. Additional digital I/O can be supported be many cards. SCSI adaptors are available from several manufacturers which may be used as the DSA.

The DSP Coprocessor and its A/D and D/A Modules must be developed to meet the needs of the MACE architecture. The DSP chip recommended is the Texas Instruments TMS320C30 Third Generation Digital Signal Processor; this chip boasts an impressive list of features; see Section 1.2.3 above for some of the most pertinent.

Software

Software development is easily performed on IBM PC-AT class machines. A list of software tools required, as well as estimated costs, follows.

GENERAL TOOLS

- Text editor (Brief by Solution Systems) List $200
- Software version control (PVCS by Polytron) List $395

PC-AT PROCESSOR TOOLS

- Compiler (C 5.1 by Microsoft) List $450
- Assembler (MASM 5.1 by Microsoft) List $150
- Debugger (CodeView by Microsoft) Included with C 5.1

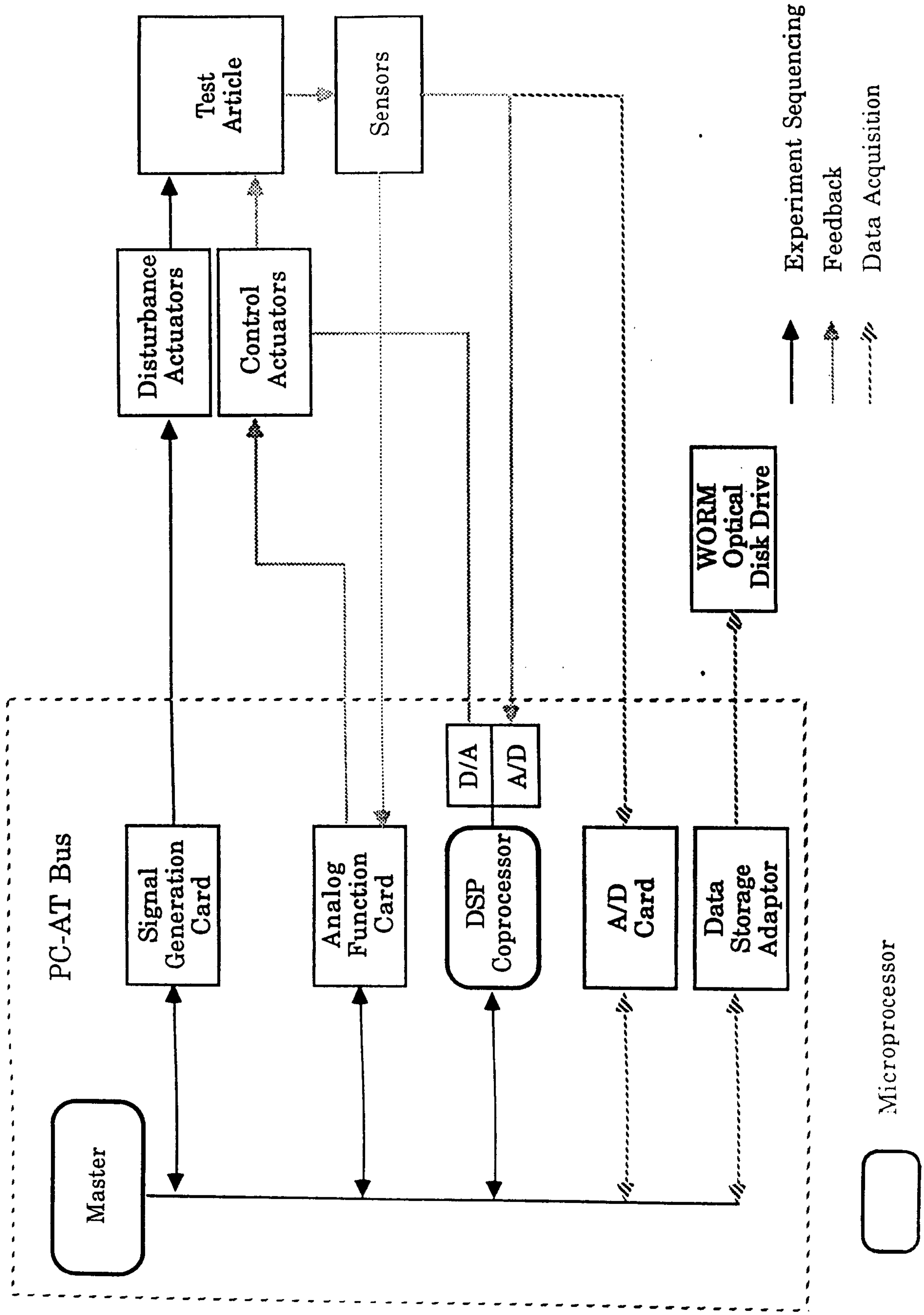


Figure C.2.1 PC/AT Architecture

DSP DEVELOPMENT TOOLS

- Compiler (TMS320C30 Optimizing C Compiler by Texas Instruments) List $2500
- Assembler (TMS320C30 Macro Assembler/Linker by Texas Instruments) Included in the TMS320C30 Optimizing C Compiler package or $500 List
- Simulator (TMS320C30 Simulator by Texas Instruments) List $1500
- Emulator (TMS320C30 Emulator (XDS1000) by Texas Instruments) List $10,000

Appendix D: Component Surveys

D.1 MBP Hardware

This section lists the requirements and specifications for the various motors and sensors which will be used as part of the MBP pointing/tracking payloads. In addition, various candidate components are presented.

D.1.1 Slewing Motors

This section sizes the slewing motors and rate gyros for the multi payload platform. The articulating payload can be modelled as a cylinder with a length of 20cm and a radius of 4cm. The moment of inertia about a diameter at one end is given by

$$I = m\left(\frac{l}{2}\right)^2 + m\left(\frac{r^2}{4} + \frac{l^2}{12}\right)$$

For a mass of 2Kg, the inertia is $0.0274 Kgm^2$.

If a slew of plus or minus 90 degrees is desired at one hertz, a torque motor of 1.25lb ft must be used. Table D.1.1 lists candidate frameless motors from the Inland Motors catalog.

Table D.1.1 Candidate frameless motors for slewing

Model	Peak torque at stall	Power	Dimension	Weight	Power for four motors
NT-2146	1.25 lb ft	75 W	2.8"ODx2.5"	3 lbs	300 W
T-5403	1.3 lb ft	120 W	6.1"ODx0.7"	1.2 lbs	480 W
T-5406	2.0 lb ft	52 W	6.1"ODx1.2"	3 lbs	208 W
QT-7602	2.1 lb ft	17 W	8.5"ODx1.3"	7.3 lbs	67 W
T-3910	1.0 lb ft	50 W	4.6"ODx0.7"	1.1 lbs	200 W
T-2719	0.5 lb ft	38 W	3.4"ODx0.7"	0.9 lbs	150 W

In a one gravity environment, the torque required to enable slewing in the vertical plane is 0.724 lb ft.

D.1.2 Rate Gyros

The angular rate corresponding to a plus or minus 90 degree slew at one hertz is 570 degrees/sec. It would be desirable to have a resolution of one thousandth of this rate or 0.57 degrees/sec. Table D.1.2 gives some representative rate gyro specifications.

Table D.1.2 Representative rate gyro specifications

Range	Accuracy	Resolution	Bandwidth
30 deg/sec	0.6 deg/sec	selectable	
40 deg/sec	1 deg/sec	selectable	20 Hz min
1000 deg/sec	25 deg/sec	selectable	20 Hz min

D.1.3 Tachometers

The specifications for the tachometers are the same as for the rate gyros. Specifically, it is desirable to have 10 Volts at 9.87 radians/sec (1.0 V/rad/sec). Table D.1.3 lists some candidate Inland Motor tachometers.

Table D.1.3 Candidate Inland Motor tachometers

Model	Sensitivity	Dimension	Weight
TG-2123	1.01 V/rad/sec	2.8"OD x 0.6"	0.56 lbs
TG-2138	2.20 V/rad/sec	2.8"OD x 1.0"	0.88 lbs
TG-2169	2.20 V/rad/sec	2.8"OD x 1.0"	0.88 lbs
TG-2179	1.20 V/rad/sec	2.8"OD x 0.6"	0.56 lbs
TG-2196	1.45 V/rad/sec	3.1"OD x 1.7"	1.50 lbs
TG-2801	1.00 V/rad/sec	3.4"OD x 0.7"	0.75 lbs
TG-2936	2.20 V/rad/sec	3.7"OD x 1.2"	1.50 lbs
TG-2916	0.85 V/rad/sec	3.7"OD x 0.9"	1.10 lbs

D.2 ADDITIONAL COMPONENTS

In addition to the payload actuation/instrumentation, the MBP and the MACE ESM will have numerous additional components: power conditioners, accelerometers, etc. The following pages list various types of components that may be part of the MACE Experimental Support Module or the MACE reference design. The final component list is given in Chapter 4. The type of components surveyed are:

- Rate Transducers
- Accelerometers
- Force Transducers
- Signal Conditioners
- Signal Generators
- Power Amplifiers
- Data Storage Devices
- Power Supplies

Initially, attention was focused primarily on those components which where "flight qualified". However, it became clear that flight qualification is not a significant barrier when dealing with components which are "off the shelf". NASA qualifies a payload as a whole, not as individual components, with the only requirement being the availability of a manufacturer-supplied materials list.

Table D.2.1 Angular Rate Transducer Survey

Manufacturer	Model #	Type	Cost	Power	Size	Weight	Performance
JAE	JG-23	Rate Gyroscope	$2,396.00	3 W max.@ 26 V(400 Hz.)	1 " dia. x 2.1" L	140 gm	Range: 40 or 100°/sec Resolution: 0.01 or 0.03°/sec
Applied Technology	IETL-001	MHD angular rate sensor	$2,600.00	240 mW @ ± 15 VDC	0.8" dia x 0.6" L	35 gm	Range: ± 91,000°/sec Sensitivity: 0.1 mV/deg/sec Freq. Resp.: 0.4 to 400 Hz Noise: 11 millidegrees equiv. across 1 to 1000 Hz BW
Humphrey	RG78-0300	Rate Gyroscope DC in/DC out	$2,500.00	7 W @ 31 VDC	2 x 3.7 x 1.8"	227 gm (8 oz)	Range: 40 to 1000 °/sec Sensitivity: ~ 1 mV/deg/sec min. Natural Freq: 20 to 140 Hz Threshold: 0.03°/sec
Humphrey	RG78-0100	Rate Gyroscope AC in/AC out	$1,800.00	4 W @ 24 VAC, 400 Hz	0.58" dia x 2.15"L	85 gm (3 oz)	Range: 40 to 1000 °/sec Sensitivity: ~ 1 mV/deg/sec min. Natural Freq: 20 to 140 Hz Threshold: 0.03°/sec
Humphrey	RT01-0606	Rate transducer	$1,270.00	168 mW @ 2.8 VDC + 18 VAC/4kHz	0.99" dia. x 1.5" L	57 gm (2 oz)	Range: ± 325°/sec Sensitivity: 0.05 mV/°/sec Natural Freq: 30 Hz min. Resolution: 0.05% of full scale
JAE	DARS	Dual axis rate transducer	$3,500.00	10 W start 2 W run	0.8" dia x 1" L	35 gm (1.2 oz)	Range: ± 100°/sec Sensitivity: 100 mV/°/sec Resolution: 0.01°/sec
Humphrey	RT09-0103	Dual axis rate transducer	$1,850.00	216 mW @ 3.6 VDC + 18 VAC/4kHz	1" dia x 2.7" L	85 gm (3 oz)	Range: ± 100°/sec Sensitivity: 0.1 mV/°/sec Natural Freq: 25 Hz min. Resolution: 0.05% of full scale

Table D.2.2 Accelerometer Survey

Manufacturer	Model #	Type	Cost	Size	Weight	Power	Response ±5%	Sensitivity	Resolution
Angular:									
Kistler	8832	PE, integral amp	$1,650.00	.62 x .62 x .48"	10 gm	~ 250 mW est.	1 to 2000 Hz	0.009 to 0.87 mV/°/sec/sec	Threshold: 34°/sec/sec
Columbia	SR207RFR	Servo	$2,295.00	1.5" dia x 3" L	142 gm	600 mW max	0 to 10 Hz min 0 to 100 Hz max	0.09 to 4 mV/°/sec/sec	Range: ± 570 to 28.6k deg/sec/sec Resolution: 1% of F.S.
Endevco	7302BM2	PR	$1,675.00	0.75" dia x 1.23" L	72 gm	50 mW typ.	10 to 200 Hz	0.87 µV/°/sec/sec	limited by pwr supply noise Range: 286,000 deg/sec/sec
Single Axis Linear:									
Endevco	7265A-HS	PR, oil damped	$890.00	0.5 x 0.5 x 0.3"	6 gm	135 mW max.	0 to 500 Hz 90° shift @ 1400Hz	25 mV/g	limited by pwr supply noise
Endevco	7290-10	Variable cap., gas damped	$940.00	1 x 0.85 x 0.25"	12 gm	225 mW max.	0 to 600 Hz 90° shift @ 3700Hz	200 mV/g	0.4 mg achieved w/ good sig. conditioners
Note: Not available in quantity until end of 1989									
IC Sensors	3110	PR (integ. amp)	$268.00	1.6 x 1.6 x 0.6"	30 gm	50 mW typ.	0 to 700 Hz 27° shift at 200 Hz	2V/range	0.1 mg typ.
Sundstrand	QA-700	Quartz servo	$995.00	1.1" dia x 0.8"L	50 gm	2.1 W max. (1.2 W quiesc.)	0 to 300 Hz 90° shift @ 2000Hz	selectable (ext. resistor)	0.001 mg
Sundstrand	Mini-Pal	Quartz servo	$1,595.00	0.5" dia x 1.4"L	20 gm	450 mW max.	0 to 350 Hz ± 3dB	selectable	For 1 g range: 0.05 mg Threshold 5 mg Repeatability
Note: Standard Mini-Pal mount is 34 gm, 1.7 x 1.3 x 0.8"									
Columbia	SA120RNP	Quartz servo	$1,295.00	1' dia x 0.7 H	~28 gm	600 mW max.	0 to ~100 Hz (±3dB) 90° shift @ 100 Hz	selectable	0.1 mg typ. (limited by conditioning circuitry)
Endevco	7751-100-X	PE (integ. amp)	$665.00	0.75" dia. x 1.2" H	40 gm	240 mW max.	0.2 to 5000 Hz ± 2°, 5 to 5000 Hz	100 mV/g	1 mg (based on ± 5 VDC output, 100 mV sensit.)
Endevco	7701-50	PE	$445.00	0.625" dia. x 0.78" H	25 gm	none	1 to 6000 Hz ± 2°, 25 to 6000 Hz	50 pC/g	limited by charge amp sensitivity, S/N ratio

Table D.2.2 Accelerometer Survey (Cont.)

Manufacturer	Model #	Type	Cost	Size	Weight	Power	Response ±5%	Sensitivity	Resolution
Triaxial:									
Columbia	SA-302MFTA	Servo	$3,595.00	3.5 x 1.4 x 1.5"	283 gm	2.5 W max.	0 to ~50 Hz (increase w/range)	selectable	~ 0.1 mg
Columbia	SA-307HPTX	Servo	$2,175.00	4 x 3 x 2.5"	340 gm	1.5 W max.	0 to ~50 Hz (increase w/range)	selectable	~ 0.1 mg
PCB	303A06	Quartz, triaxial (integ. amp)	$950.00	0.86 x 0.86 x 0.86'	22 gm	240 mW typ.	1 to 10 kHz	10 mV/g	10 mg
PCB	346A	Quartz, triaxial (integ. amp)	$1,350.00	1.1 x 1.1 x 0.75"	71 gm	560 mW typ.	2 to 2000 Hz	50 mV/g	2 mg
Entran	EGA3-F-25D	PR, triaxial	$1,249.00	0.5 x 0.5 x 0.5"	8 gm	450 mW typ.	0 to 100 Hz (0 to 1000 Hz avail)	12 mV/g	limited by pwr supply noise (10 mg typ.)

Table D.2.3 Torque Motor Survey

Manufacturer	Model #	Cost	Size	Weight	Peak Torque at Stall	Power at Stall
Inland Motors	NT-2146	$2,210.00	2.8" dia x 2.5" H	3 lbs	1.25 lb ft	75 W
Inland Motors	T-5403	$2,350.00	6.1" dia x 0.7" H	1.2 lbs	1.3 lb ft	120 W
Inland Motors	T-5406	$2,405.00	6.1" dia x 1.2" H	3 lbs	2.0 lb ft	52 W
Inland Motors	QT-7602	$4,740.00	8.5" dia x 1.3" H	7.3 lbs	2.1 lb ft	17 W
Inland Motors	T-3910	$1,370.00	4.6" dia x 0.7" H	1.1 lbs	1.0 lb ft	50 W
Inland Motors	T-2719	$1,395.00	3.4" dia x 0.7" H	0.9 lbs	0.5 lb ft	38 W

Table D.2.4 Force Tranducer Survey

Manufacturer	Model #	Type	Cost	Size	Weight	Power	Frequency Response ±5%	Sensitivity
PCB	208	Quartz, stud or bolt mount (internal amp)	$350.00	0.5" dia., 0.63"H	25 gm.	30 to 300 mW (2 to 20 mA CC)	0.3 mHz to 21 kHz	10 mV/lb
PCB	209	Quartz, stud or bolt mount (internal amp)	$385.00	0.4" dia., 0.6 H	8 gm.	30 to 300 mW (2 to 20 mA CC)	0.5 Hz to 100 kHz	2.2 V/lb
Entran	ELF series	Quartz, Flatline, various mounting types	$400 to $600	1" dia typ., 0.2" H typ.	~5 gm	150 mW@ 15 VDC	DC to 1500 Hz (up to 8 kHz avail)	5 mV/lb
Entran	ELH series	Quartz, stud mount or load cell type	~ $800.00	0.4" dia.,0.4" H (w/o studs)	~10 gm	150 mW@ 15 VDC	DC to 1400 Hz (up to 5 kHz avail.)	10 mV/lb
Entran	ELM-600A	Quartz, internal amp, load cell type	$805.00	0.6"dia., 0.2"H	~5 gm	300 mW@ ±15 VDC	DC to 2 kHz (up to 12 kHz avail)	500 mV/lb
Entran	MLGL-50	Quartz, hole mount, high accuracy model	$966.00	1 x 1.6 x .67"	~125 gm	50 mW @ 5 VDC	DC to 1100 Hz	2.7 mV/lb
Schaevitz	FTD-G Series	LVDT, stud mount (DC powered, high level out)	$761.00	0.75" dia., 1.9" H (w/ studs)	227 gm.	450 mW (Battery pwr OK)	DC to 50 Hz	227 mV/lb

Table D.2.5 Signal Conditioner Survey

Manufacturer	Model #	Type	Cost	Power	Size	Weight	Performance
For Rate Transducers:							
Humphrey	PS27-0101	26 V, 400 Hz Power supply 27.5 VDC input	$855.00	47 W max delivered	3.25 dia. x 4.5" L	1.5 lb (0.68 kgm)	400 Hz single phase square wave output
For Strain Gauges:							
Analog Devices	1B31AN	Integrated circuit strain gauge conditioner	$69.00	300 mW (quiescent)	28 pin DIP	~ 1 gm	Gain: 2 to 5000 V/V, 2-pole active filter, adjustable transducer excitation
For Accelerometers:							
PR types:							
Entran	IM Series	For PR type tranducers	$350.00	20 mA @ 28 V (unreg)	1.2 x 1.4 x 2.5"	114 gm	Gain fixed or adjustable, 1 to 1000;current or voltage outputs (4-20 mA, 0-5V, 0-10V)
PE types:							
Endevco	2680	Airborne charge amp for PE transducers (charge mode to low-Z)	$1,065.00	560 mW @ 28 VDC	1.5 x 1 x .75"	34 gm	Gain adjustable (range of factor of 10); available 0.1 to 100 mV/pC
PCB	413	In-line, fixed gain (charge mode to low-Z)	$235.00	28 mW @ 24 VDC	0.5" dia. x 2.6" L	20 gm	Gain = 10; output = ± 5VDC; 1 mV p-p noise
Columbia servo types:							
Columbia	5692	Unity gain buffer for use with servo (constant current mode) transducers	$249.00	~ 28 mW @ 28 VDC	0.125" cube	~ 1 gm	± 5 VDC full scale output

Table D.2.5 Signal Conditioner Survey (Cont)

Manufacturer	Model #	Type	Cost	Power	Size	Weight	Performance
Accelerometers, cont'd							
For PCB triaxials:							
PCB	495B02	Power unit and amplifier (use with PE types with integral amps)	$510.00	392 mW @ 28 VDC	0.9 x 1.1 x 1.5"	50 gm	28 VDC transducer excitation at 2 mA; Gain adjustable 1-25; ±3dB 3-2000 Hz.
PCB	485B	Power conditioner for PE's with internal amps	$55.00	240mW max. @ 24 VDC	0.7 x 1.5 x 3"	40 gm	16-20VDC transducer excitation at 2 -20 mA

NOTES:

1. Other servo accelerometer types require ± 15 VDC and provide ± 5VDC full scale output.
2. PR types require well regulated DC voltage and provide high level (~ 2VDC) output.
3. Variable capacitance types require 13 to 18 VDC (unregulated) and provide 2 VDC full scale output.

Table D.2.5 Signal Conditioner Survey (Cont)

Manufacturer	Model #	Type	Cost	Power	Size	Weight	Performance
For Force Transducers:							
For PCB 208 and 209:							
PCB	485B	Power conditioner for PE's with internal amps	$55.00	240mW max. @ 24 VDC	0.7 x 1.5 x 3"	40 gm	16-20VDC transducer excitation at 2 -20 mA
Note: Same unit as for PCB PE accelerometers.							
For Entran devices:							
Entran	IM Series	For PR type tranducers	$350.00	20 mA @ 28 V (unreg)	1.2 x 1.4 x 2.5"	114 gm	Gain fixed or adjustable, 1 to 1000;current or voltage outputs (4-20 mA, 0-5V, 0-10V)
Note: Same unit as for PR type accelerometers.							
For Schaevitz LVDT:							
Schaevitz DC LVDT types require only ± 15 VDC, unregulated supply, and provide ± 5 VDC full scale output.							
General purpose:							
PCB	401 or 402	Voltage follower; in-line or connector type (charge mode to low-Z)	$110.00	24 mW @ 24 VDC	0.25" dia x 1.14" L	3 gm	±5 VDC input range; 250 µV p-p noise

Table D.2.6 Signal Generator Survey

Manufacturer	Model #	Type	Cost	Power	Size	Weight	Performance
Sciteq	VDS-8	Direct digital frequency synthesizer	$1,250.00	6 W max. (+5,±12 VDC)	4.5" x 6.5" (circuit card)	<8 oz.	1 mHz steps, DC to 80 kHz, requires 12 bit TTL word input and sequence controller
Sciteq	VDS-8-PC	VDS-8 on PC bus card	$2,000.00	~ 7W	4.7" x 13.3"	<8 oz.	On board control program; programmable sweeps; available 6/89
Negative Feedback	1930	Function generator	$2,400.00	40 W*	14" x 8.5" x 5"	11 lb.*	1 mHz steps, 1 mHz to 1.2 Mhz programmable sweep mode,

* Specified for AC powered unit; modification required for DC operation

Table D.2.7 Power Amplifier Survey

Manufacturer	Model #	Type	Cost	Power	Size	Weight	Performance
Apex	PA04	Power op amp (for single ended operation)	$46	48 W max (delivered)	12 pin power DIP	(heat sink dominates)	±90 V at ±20 A into 5 ohms, 50 V/μs slew rate
Apex	PA21	Dual Power op amps (for bridge mode operation)	$42.00	36 W max (delivered)	8 pin TO-3	(heat sink dominates)	± Vs-1V at 3 A 1.2 V/μs slew rate

Notes: Both approaches require digital control of gain, using custom designed circuitry.

Table D.2.8 Data Storage Survey

Manufacturer	Model #	Type	Cost	Power	Size	Weight	Performance
TEAC	HR-40	9 Channel, Phillpis type FM (analog) cassette tape	$5,460.00	0.72 W (@ 9VDC)	6 x 2 x 4"	1.3 lb.	DC to 1.250 kHz Freq. Resp. @ 1-7/8 ips; 45 min record time per tape
Note: Requires separate ground playback unit.							
Mountain Optech	SEL-2	Optical Disc (WORM) drive	$7,149.00	27W	7"x 8"x 11.4"	9.8 lb.	200 Mbytes/side, 195 msec access time space qualified version available
Note: Requires Drive control processor with SCSI interface.							
TEAC	RD-111T	8 Channel PCM DAT	$9,800.00	24W (@ 12 VDC)	11 x 11 x 3"	15.4 lb.	DC to 5 kHz Freq. Resp. 16 bit quantization; 2 hr. record time/tape
TEAC	V250AB-R	1/4" video cassette	$13,500.00	12 W	6" x 5.5" x 4"	6.6 lb.	60 min. rec. time per tape; ruggedized for flight; requires input interface.

Note: V250AB-R requires commercially available input conditioning circuit.

Table D.2.9 Power Supply Survey

Manufacturer	Model #	Type	Cost	Power	Size	Weight	Outputs
International Power Devices	RWT2405-12	Metal encapsulated, DC to DC converter, triple outputs	$200.00	55 W max.	3.5 x 5.5 x 1.3"	1 lb.	+ 5V @ 5 A; + 12 V@ 1.2A; -12V @ 1.2A 81% efficiency; ±2% load regulation
International Power Devices	RWT2405-15	Metal encapsulated, DC to DC converter, triple outputs	$200.00	55 W max.	3.5 x 5.5 x 1.3"	1 lb.	+5V @ 5A; +15V @ 1A; -15V @ 1A 81% efficiency; ±2% load regulation
International Power Sources	DCC-204	Metal case, DC to DC converter, single output, MIL 217D (high MTBF)	$119.00	50 W max.	3.8 x 6.3 x 1.3"	14.4 oz	+ 24V @ 2.5A; 75% efficiency typ.; ± 0.9% load regulation

Appendix E: Computers

The real time processor is the heart of the MACE instrumentation. To determine the required size of the MACE real time processor, the operational frequencies of the structure are required, the number of floating point operations must be determined and the amount of required memory must be calculated. The probable feedback laws are

$$u_i = -Fy_i + u_{r_i} \quad \textit{output feedback} \tag{1}$$

$$\begin{aligned} u_i &= -F\hat{x}_i + u_{r_i} \quad \textit{full state feedback with estimator} \\ \hat{x}_{i+1} &= [A - KC]\hat{x}_i + [B - KD]u_i + Ky_i \end{aligned} \tag{2}$$

$$\begin{aligned} u_{i+1} &= C\hat{x}_i + Dy_i \quad \textit{in general and canonical forms} \\ \hat{x}_{i+1} &= A\hat{x}_i + By_i \end{aligned} \tag{3}$$

The number of operations required for each of the control algorithm forms needs to be determined. Table E.1 lists the number of multiplies, additions, stored data values (gains) and stored variables (states, inputs and outputs). The input vector u has dimension mx1. The output vector y has dimension px1. The estimated state vector x has dimension nx1. The reference input vector has dimension qx1.

Table E.1 Required number of multiplies, additions, stored values and stored variables

Algorithm	Multiplies	Additions	Stored values	Stored variables
(1) output feedback	mp	m(p-1)+q	mp+p+q+m	m+p
(2) full state w/est.	2mn+n^2+np	m(n-1)+q+n(n-1) +nm+np	2mn+2m+3n +q+p+n^2+np	2m+3n+p
(3) general	mn+mp+n^2 +np	(m+n)(n+p-1)	mn+mp+n^2 +np+m+3n +2p	m+3n+2p
(3) output canonical	mp+n+np	mp+n+np-1	(m+n)p+m +4n+2p	m+3n+2p
(3) input canonical	mn+mp+n	m(n-1)+mp +p+n-1	mn+mp+m +2p+4n	m+3n+2p

Table E.2 shows the various cases for which the processor parameters are evaluated. The various parameters are given in Table E.3 for various control algorithms. Finally, in Table E.4, typical A/D and D/A conversion speeds and channel numbers are given.

The input canonical form is more efficient than output canonical form when m<p. This is typically the case. However, canonical forms can be numerically error prone.

Table E.2 Various cases for evaluation of the processor parameters

Case	m	n	p	q
(a)	1	4	2	0
(b)	4	32	8	0
(c)	8	64	16	0
(d)	2	4	1	0

Table E.3 Required processor parameter values for various cases

Algorithm	Case	Mult	Add	Values	Variables
(1) output	(a)	2	1	3	5
	(b)	32	28	12	44
	(c)	128	120	24	152
	(d)	2	0	3	5
(2) FS w/est	(a)	32	27	16	48
	(b)	1536	1500	112	1648
	(c)	6144	6072	224	6368
	(d)	36	30	17	53
(3) general	(a)	30	25	17	47
	(b)	1440	1404	116	1556
	(c)	5760	5688	232	5992
	(d)	28	0	16	46
(3) output	(a)	14	13	17	31
	(b)	320	319	116	436
	(c)	1216	1215	232	1448
	(d)	10	9	16	26
(3) input	(a)	10	10	17	27
	(b)	192	195	116	308
	(c)	704	711	232	936
	(d)	14	12	16	30

Table E.4 A/D and D/A conversion

		minimum	typical	maximum
A/D	# channels	4	16	32
	speed (Hz)	200	400	1000
D/A	# channels	2	8	16
	speed (Hz)	200	400	1000

conversion should not occupy more than 30% of control cycle period